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U.S. DEPARTMENT OF ENERGY

USPAS - Fundamentals of Ion Sources
16. Electron Beam Ion Sources/Traps (EBIS/EBIT)

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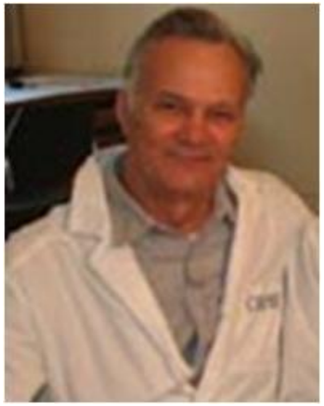
Massachusetts Institute of Technology

Content

EBIT/EBIS Ion sources

- EBIT Ion Source Fundamentals - Brief History
- Key Concepts
- Some examples of Electron Beam Ion Sources (EBIS)
- Main physics processes in the EBIT Source
  - Electron Beam
  - Charge Balance – optimizing for the desired charge state
  - Ionization potential and final charge state in an EBIS/EBIT
  - Trap Capacity
  - Vacuum Considerations
- Ion extraction
- (if time) ReAccelerator charge breeder

Electron Beam Ion Sources



Evgeni Donets, Dubna

- 1967 first proposed – developed at about the same time as ECR ion sources (Donets is one of the pioneers)
- Driven by the need to use high charge states to increase the final energy for the accelerator

$$LINAC \qquad \frac{E}{M} = \frac{Q}{M} \cdot e \cdot V$$

$$Cyclotrons \qquad \frac{E}{M} = \frac{Q^2}{M} \cdot K, K = \frac{(B \cdot \rho \cdot e)^2}{2}$$

- Readings and materials for the lecture
  - **Currell, F. and G. Fussmann**, *Physics of Electron Beam Ion Traps and Sources.* IEEE Transactions on plasma science, 2005. **33**(6).
  - **G. Zschornack, M. Schmidt, and A. Thorn**, *Electron Beam Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.
  - **Donets**, E.D., *Electron Beam Ion Sources*, in *The Physics and Technology of Ion Sources*. 1989, I. Brown, Wiley-VCH Verlag GmbH & Co. KGaA.
  - **Wenander**, F.J.C., *Charge Breeding of Radioactive Ions*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.
  - **Wenander**: RexEBIT http://cds.cern.ch/record/478399/files/open-2000-320.pdf?version=1

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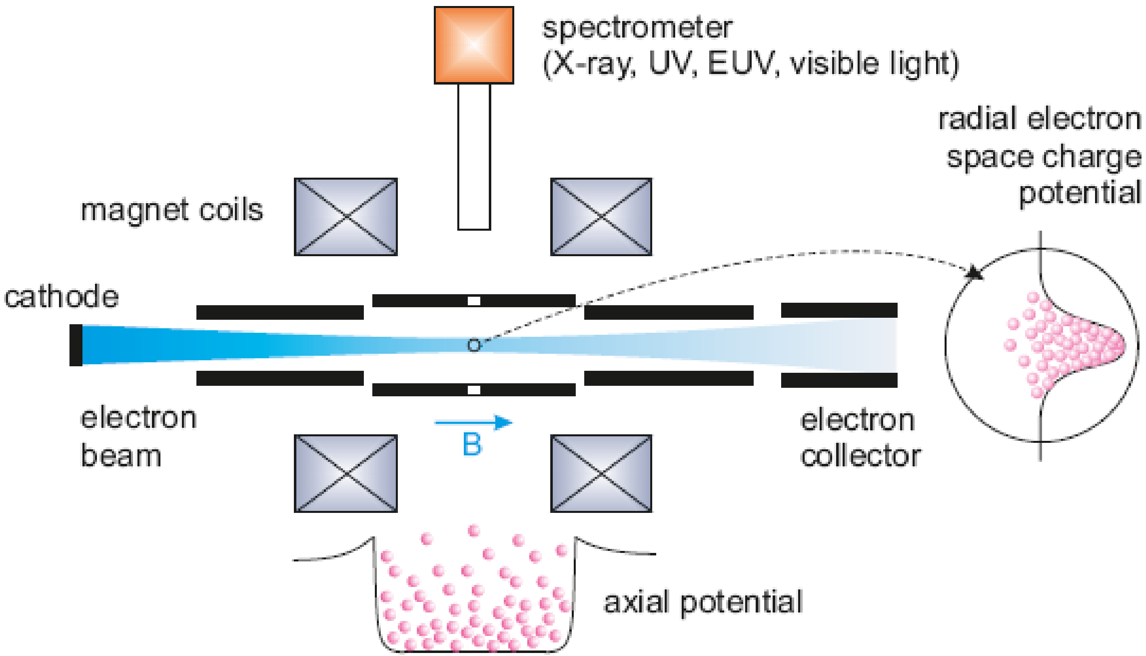
Key Concepts – physical basis of operations

1) Production of an extended electron beam of a given energy (Ionization Energy!, High electron density!)
2) Creation of an electrostatic trap for the ions while they get ionized by step-by-step ionization (Confinement Time!)
3) Injection of a defined number of low charge state ions or injection of neutrals into the trap (vapor/gas)
4) Extraction of the ions when the desired charge state is reached (pulsed operation - mostly)
5) Electron dump (collector): controlled way to dump the electron beam after it passes through the trap

EBIS do not operate with a plasma discharge!

EBIT Ion sources – main concept



Electron beam	radial confinement and breeding – successive electron impact ionization
Magnetic field	compression of electron beam
Trap electrodes	axial confinement

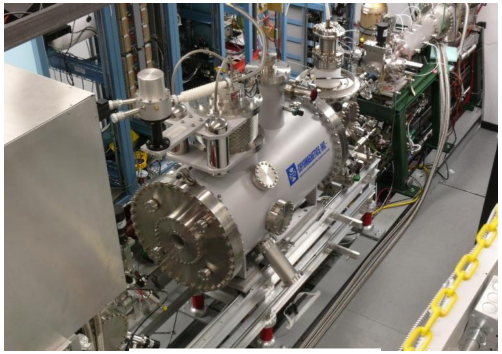
arXiv:1411.2445 ; CERN-2013-007
G.Zschornack, M.Schmidt and A.Thorn

EBIT overview

- Development today: family of ion sources, warm magnets, permanent magnets, superconducting
- **Atomic physics** groups, x-ray generator, calibration, spectroscopy
- **Injector for synchrotrons: RHIC**
- **Charge Breeder for post –accelerators (Rex-Isolde (CERN), CARIBU (ATLAS, ANL), ReA (FRIB/NSCL, MSU))**

Superconducting magnets

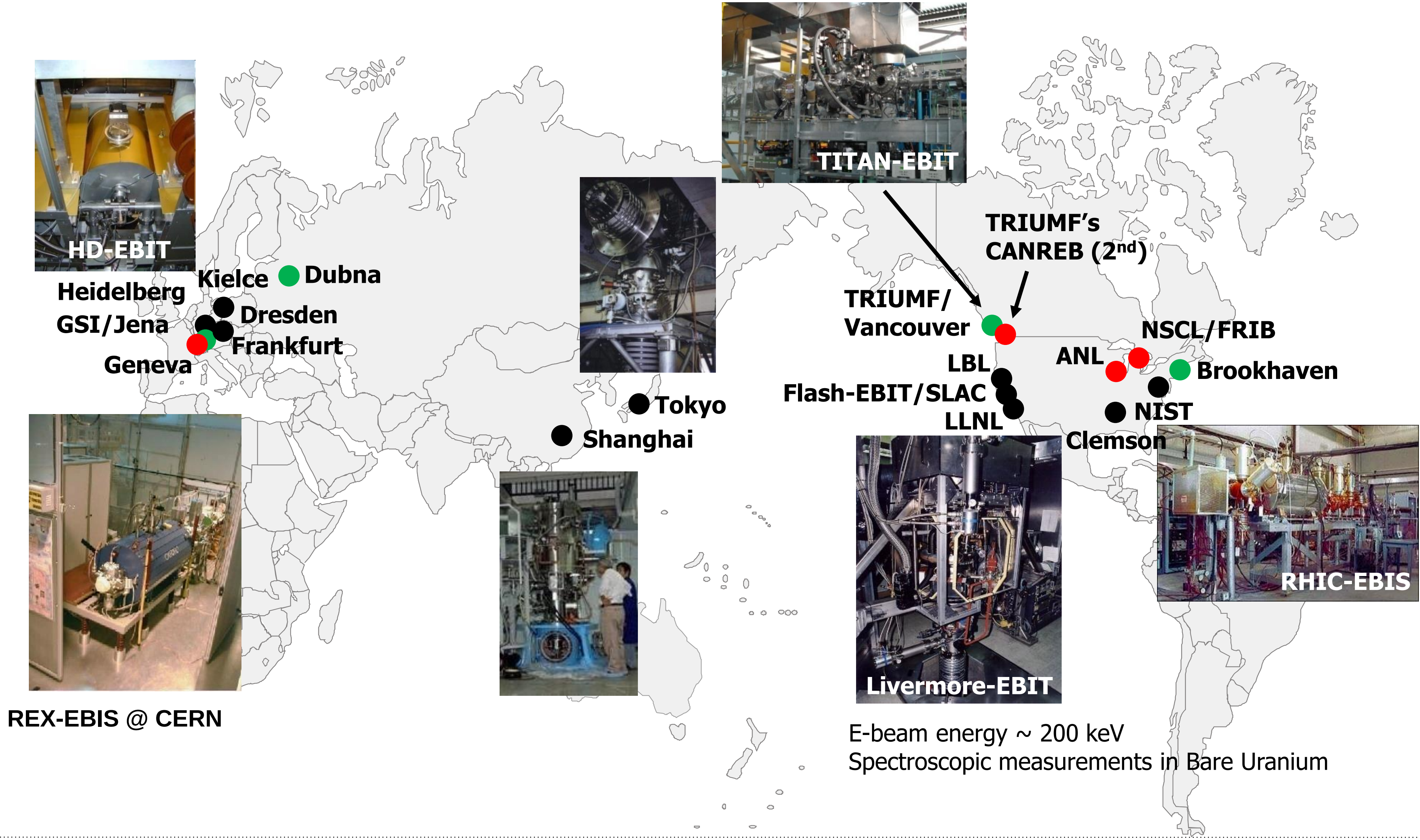
Permanent magnet



ReA EBIT

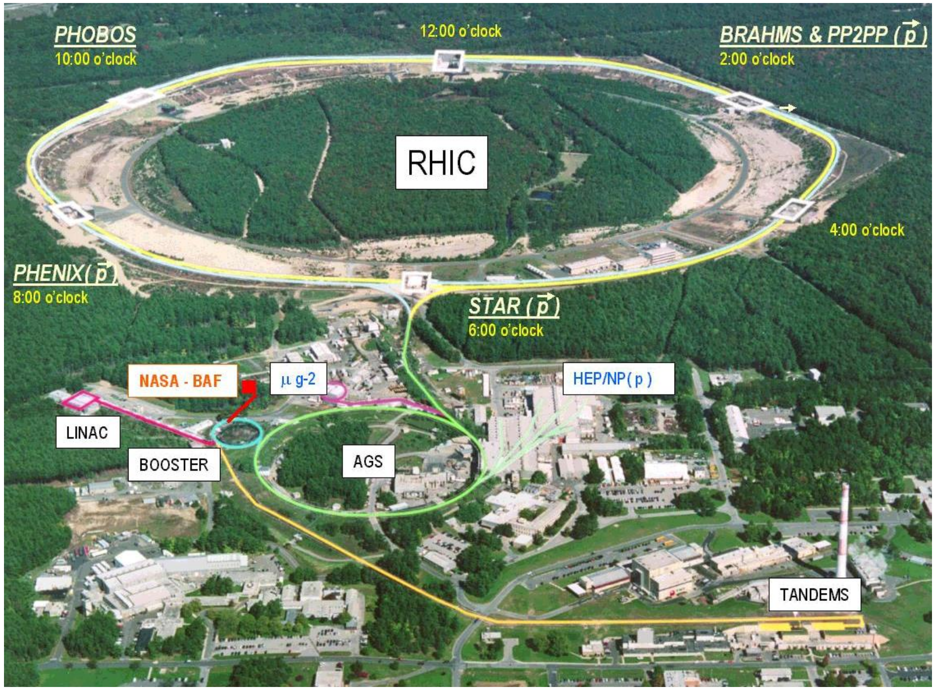
LLNL EBIT

Many EBIS/T around the world…



E-beam energy ~ 200 keV
Spectroscopic measurements in Bare Uranium

RHIC: Relativistic Heavy Ion Accelerator (collider)



- 2 independent intersecting storage rings with 6 interaction points
- Can circulate heavy ions or protons

Chain of accelerators

- 3 injectors (High charge state injector (EBIS source+linac), Tandem injector, proton linac)
- Booster Synchrotron
- Alternating Gradient Synchrotron
- 2.4 miles circumference storage ring

EBIS is an ideal source for synchrotrons because of the sharp pulse structure of the beam produced

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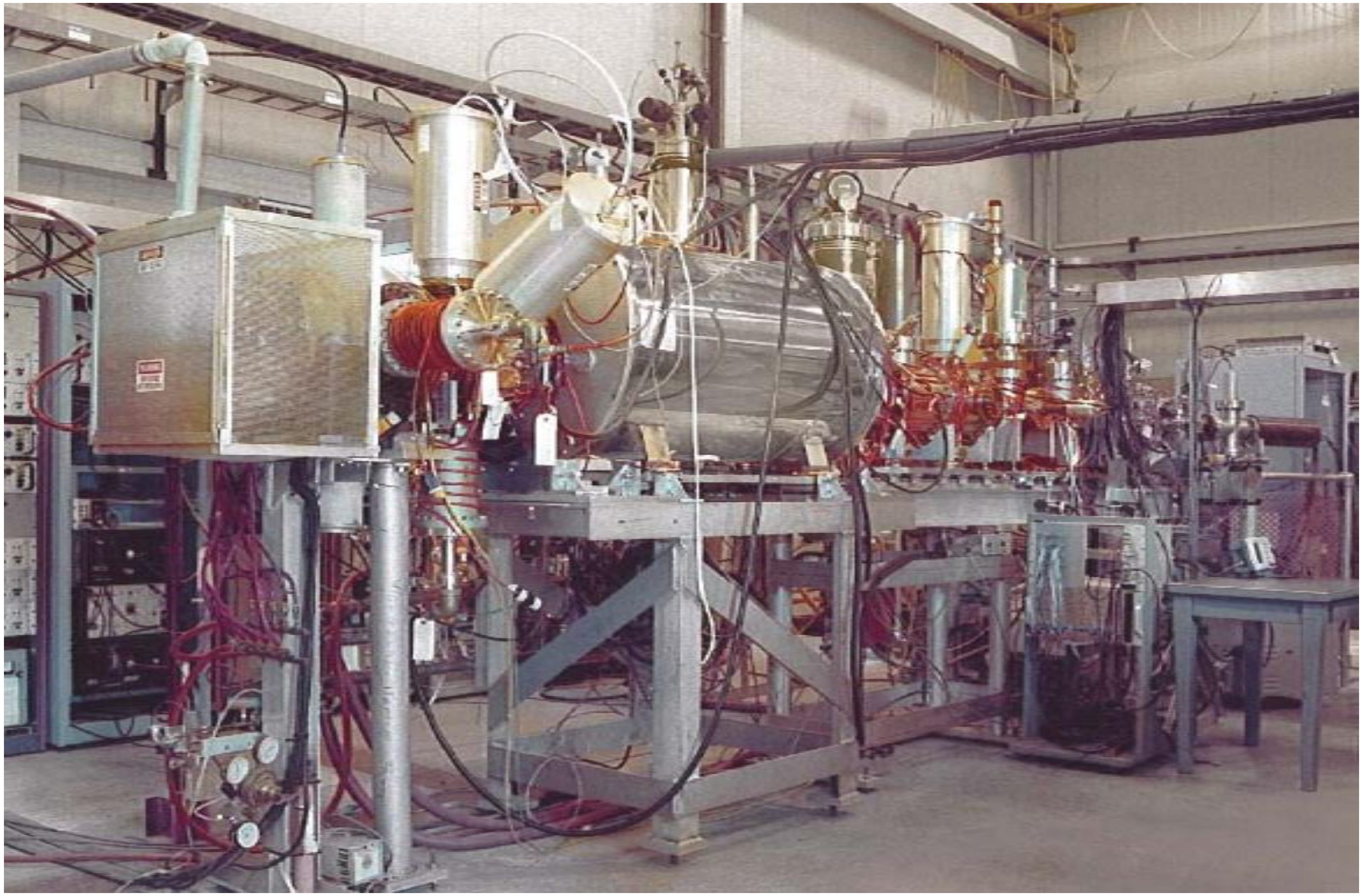
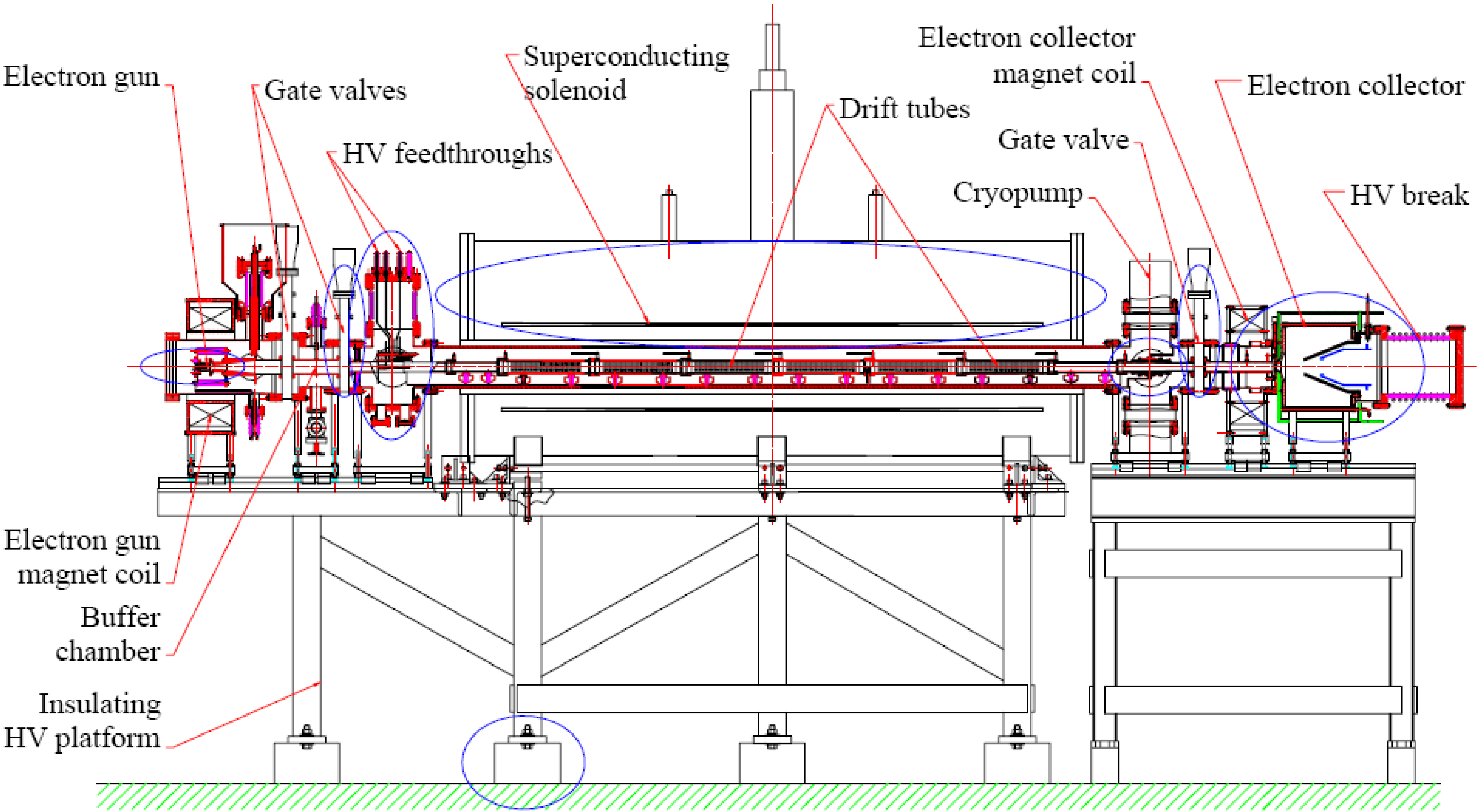
EBIS test stand facility at RHIC

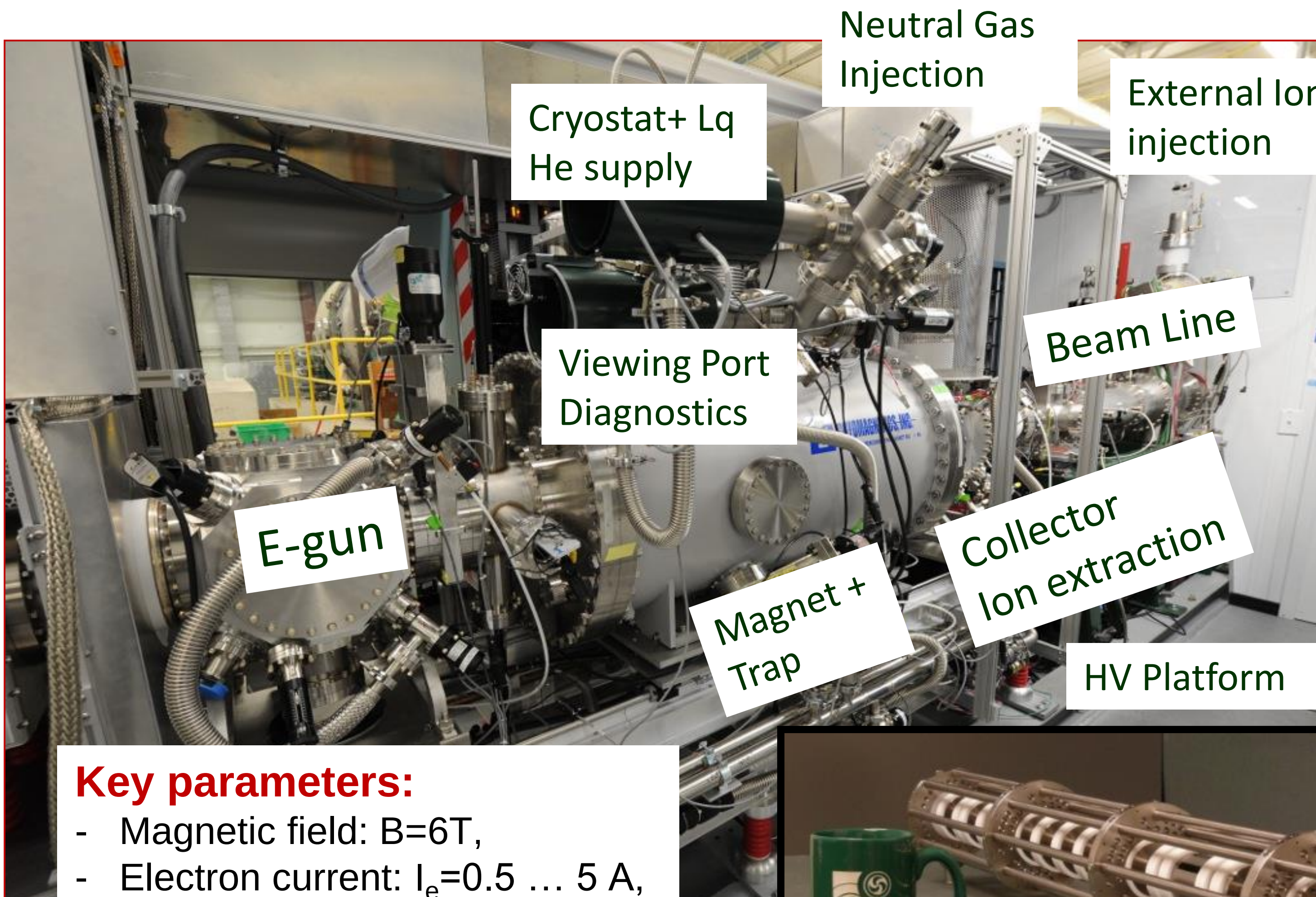


BNL EBIT cross Section

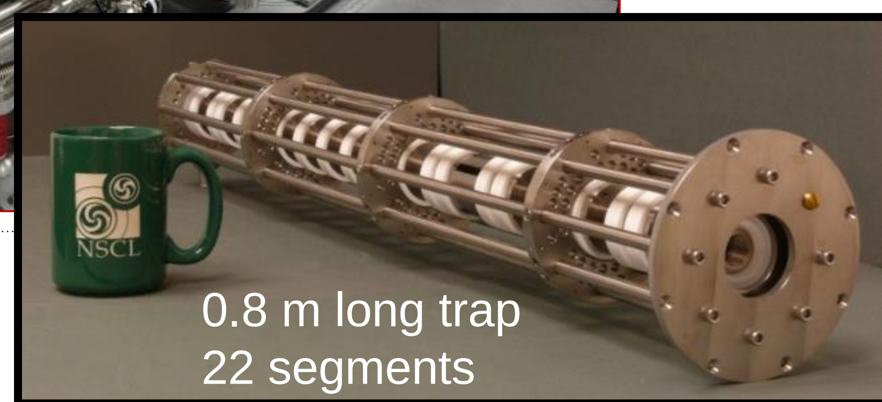


https://www.bnl.gov/cad/accelerator/docs/pdf/EBISDesignReportI.pdf

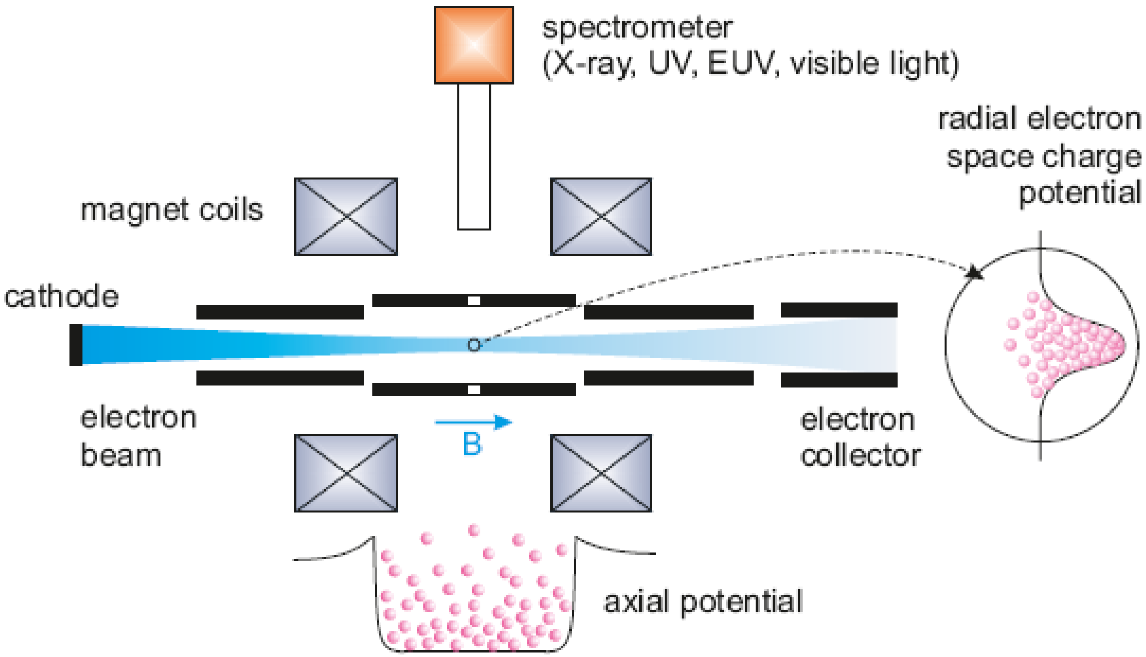
ReA EBIT Charge Breeder



Key parameters:
- Magnetic field: B=6T,
- Electron current: I_e=0.5 … 5 A,
- Electron energy: E_e < 30 keV
- Current density: j ~ 10^4 A / cm^2
- Trap Length: 635 mm



EBIT Ion sources – main concept



Electron beam	radial confinement and breeding – successive electron impact ionization
Magnetic field	compression of electron beam
Trap electrodes	axial confinement

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arXiv:1411.2445 ; CERN-2013-007
G.Zschornacka,b, M.Schmidtb and A.Thornb

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EBIT Ion sources – main concept

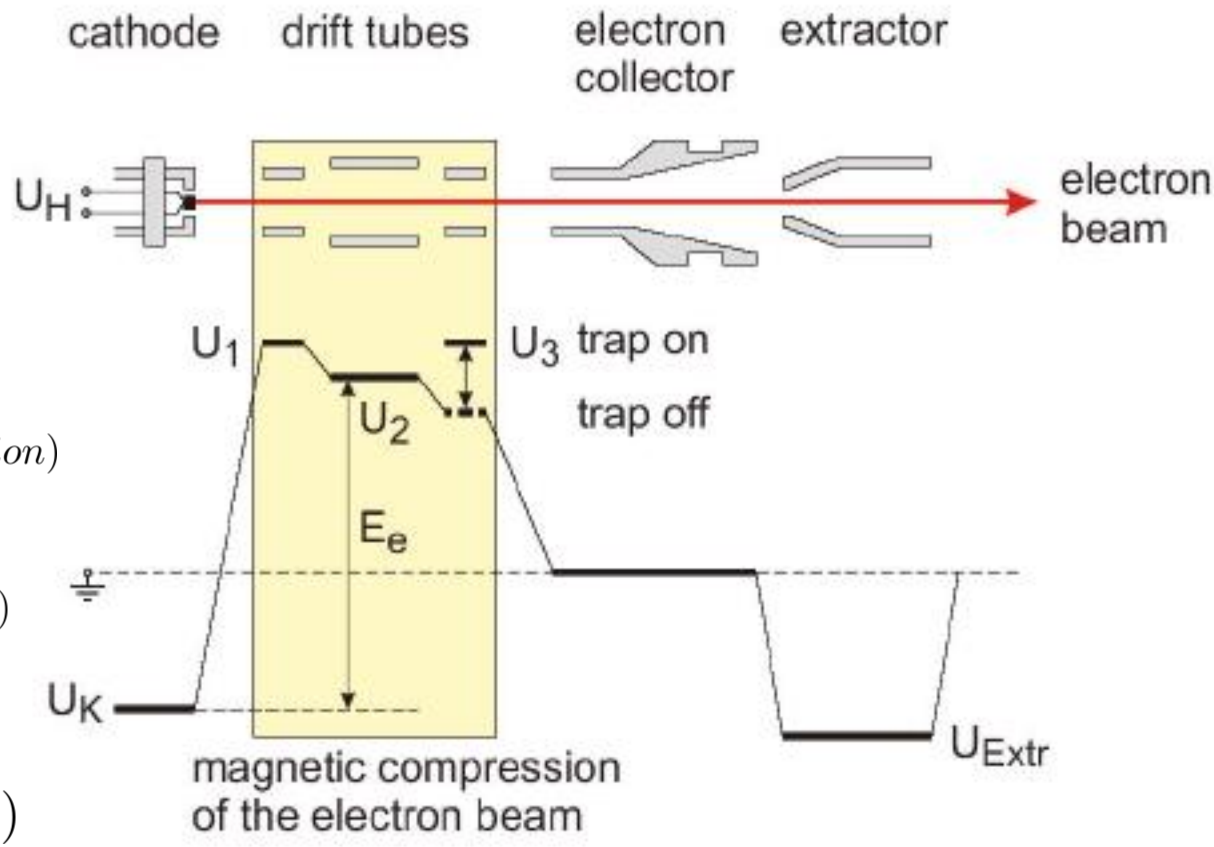
$U_1 ... Trapping\,Potential(e-gun)$

$U_2 ... Middle\,Electrode\,Potential$

$U_3 ... Trapping\,Potential\,(Extraction)$

$U_k ... Cathode Potential(neg)$

$U_{sp} ... Space\,Charge\,Potential(neg)$



$$U_{elec} = e \cdot (U_2 - U_k + U_{sc})$$

$$U_{elec}\,ranges\,from\,500\,eV\,to\,200\,keV$$

arXiv:1411.2445 ; CERN-2013-007
G.Zschornack, M.Schmidt and A.Thorn

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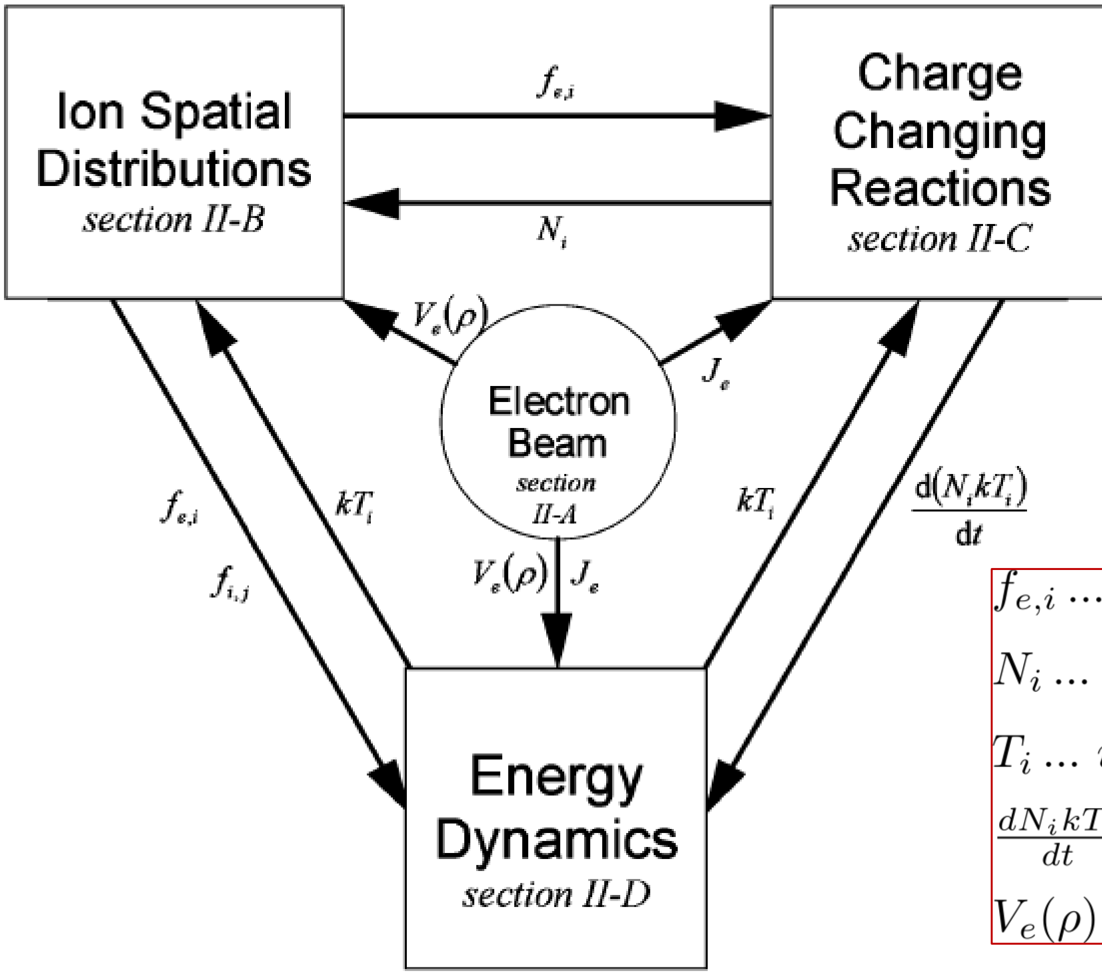
Summary of relationships of processes in an EBIS/T*



Parameters

$f_{e,i}$ ... *electron ion overlap factor*

N_i ... *ion density*

T_i ... *ion temperature*

$\frac{dN_i kT_i}{dt}$ ... *ion density change rate*

$V_e(\rho)$ ... *trapping potential*

***Currell, F. and G. Fussmann**, *Physics of Electron Beam Ion Traps and Sources.* IEEE Transactions on plasma science, 2005. **33**(6).

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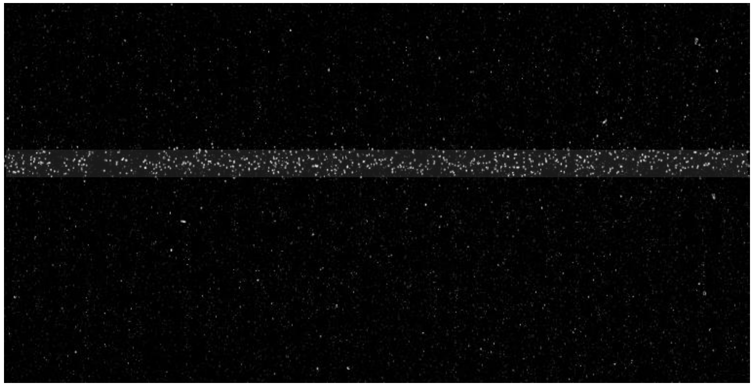
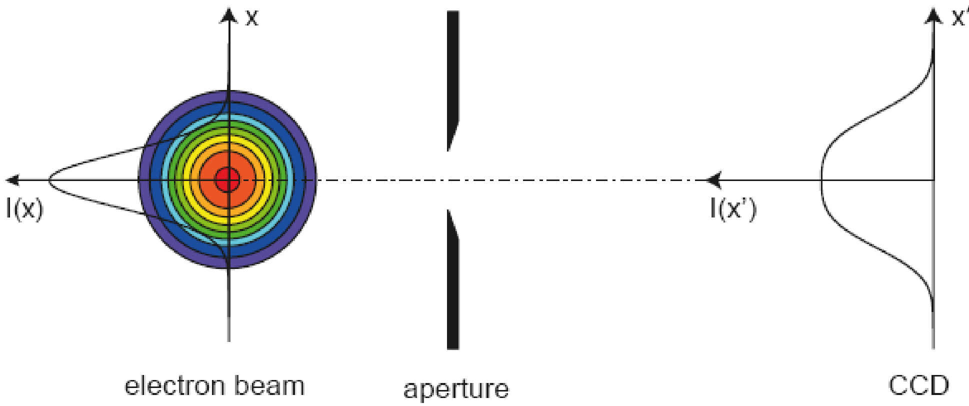
EBIS: Main Processes

The electron beam drives all atomic physics processes and are all interrelated

- **Charge Dynamics** - Processes which lead to trapped ions being created, changing charge state or lost from the trap
- **Energy Dynamics** - Processes that change the characteristic temperature of the ions in the trap (kT_i)
- **Ion Spatial Distribution** - Location of trapped ions (one for each charge state)
  - Need to define an overlap function between the electron beam and the ion cloud, driven by ion temperature!

X-ray image of the electron beam in the ReA EBIT





Electron Beam

Electron Beam/ Radial Confinement

- Ideal flow (Brillouin Flow) is established by a nearly parallel beam, with $T_e = 0$, $B_{cathode} = 0$
- Shape of the cathode is optimized to counteract the space charge of the electron beam (e.g Pierce angle)
- Upper limit for compression is given by the Brillouin Radius

$$r_b[\mu m] = \frac{150}{B[T]}\sqrt{\frac{I_e[A]}{\sqrt{E_e[keV]}}}$$

- Adding T_e, $B_{cathode}$ → Herrmann Radius (see original paper for derivation)

$$r_h = r_b\sqrt{\frac{1}{2} + \frac{1}{2}\sqrt{1 + 4\left(\frac{8kT_c r_c^2 m}{e^2 r_b^4 B^2} + \frac{B_c^2 r_c^4}{B^2 r_b^4}\right)}}$$

80% of the beam is within r_h

Typical beam sizes are 30 to 100 µm

Herrmann, G., *Optical Theory of Thermal Velocity Effects in Cylindrical Electron Beams.* Journal of Applied Physics, 1958. **29**(2): p. 127-136.

Radial Trapping potential

$$V_{\mathrm{e}}(r) = \begin{cases} \dfrac{U_{\mathrm{e}} r^2}{r_{\mathrm{e}}^2} & \text{for } r < r_{\mathrm{e}}, \\ U_{\mathrm{e}}\left(2\ln\dfrac{r}{r_{\mathrm{e}}} + 1\right) & \text{for } r > r_{\mathrm{e}}. \end{cases}$$

Potential inside the electron beam

Potential outside the electron beam

$$U_{\mathrm{e}} = \frac{I_{\mathrm{e}}}{4\pi\varepsilon_0 v_{\mathrm{e}}} = \frac{1}{4\pi\varepsilon_0}\sqrt{\frac{m_{\mathrm{e}}}{2}}\frac{I_{\mathrm{e}}}{\sqrt{E_{\mathrm{e}}}}.$$

Total charge/unit lengths of the trap

$$U_{\mathrm{e}}\left(\mathrm{V}\right) = \frac{30I\left(\mathrm{A}\right)}{\sqrt{1 - \left(\dfrac{E_{\mathrm{e}}\left(\mathrm{keV}\right)}{511} + 1\right)^{-2}}}.$$

Convenient calculating tool

The trapping potential is partially compensated by the ion cloud

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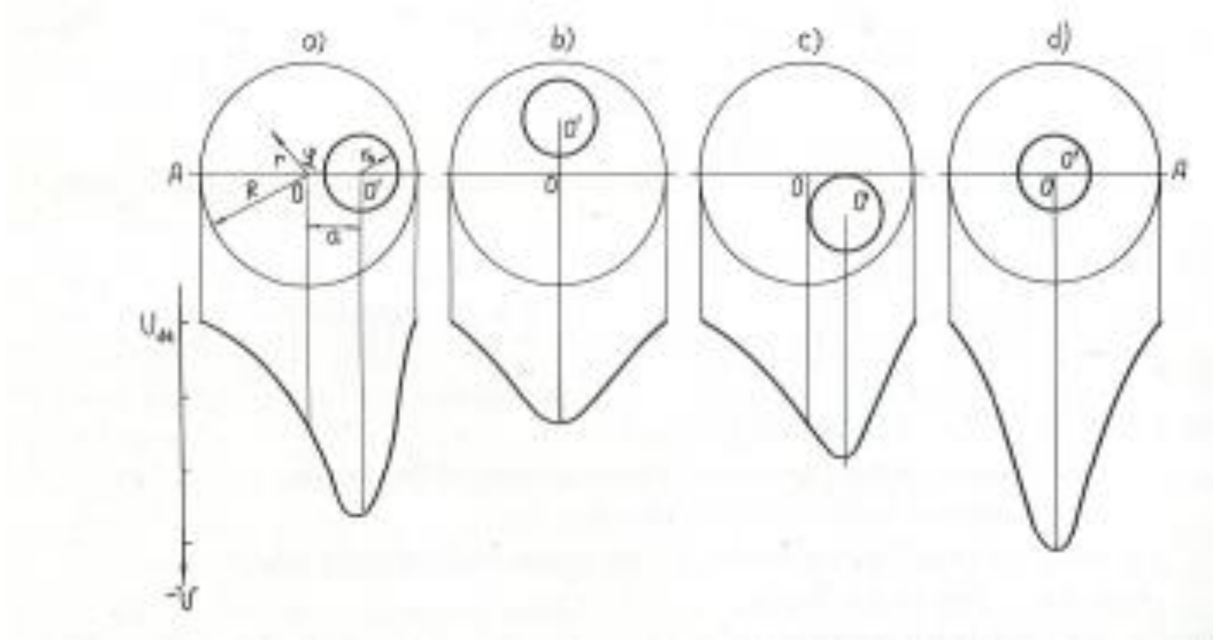
Additional variation for the trapping potential are being caused by misalignment of the magnet to the drift tube

- If the drift tubes are misaligned – the trapping potential is reduced



Donets, E.D., *Electron Beam Ion Sources*, in *The Physics and Technology of Ion Sources*. 1989, I. Brown, Wiley-VCH Verlag GmbH & Co. KGaA

Wenander: RexEBIT http://cds.cern.ch/record/478399/files/open-2000-320.pdf?version=1

Radial trapping potential and electron ion overlap function

- The trapping potential is partially compensated by the ion cloud

$$V(\rho) = V_e(\rho) + \sum_{i,\alpha} V_i(\rho)$$

Sum over all ions with i the CS and α the ion species

- The ion distribution of the electron beam can be described by a Boltzmann distribution

$$n_i(\rho) = n_i(0) e^{-(q_i V(\rho)/kT_i)}$$

- Now we can calculate *V(ρ)*

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial V(\rho)}{\partial\rho}\right) = \Theta(r_e - \rho)\left(\frac{4V_0}{r_e^2}\right) - \frac{1}{\varepsilon_0}\sum_i q_i n_i(0)\exp\left(-\frac{q_i V(\rho)}{kT_i}\right)$$

- The spatial distribution leads to the definition of an overlap function between the ions and the electron beam – which defines the probability of ionization

$$f_{e,i} = \frac{N_i^{in}}{N_i}$$

- N_i^{in} is proportional to the ion temperature! Hotter ions will spend less time in the beam!

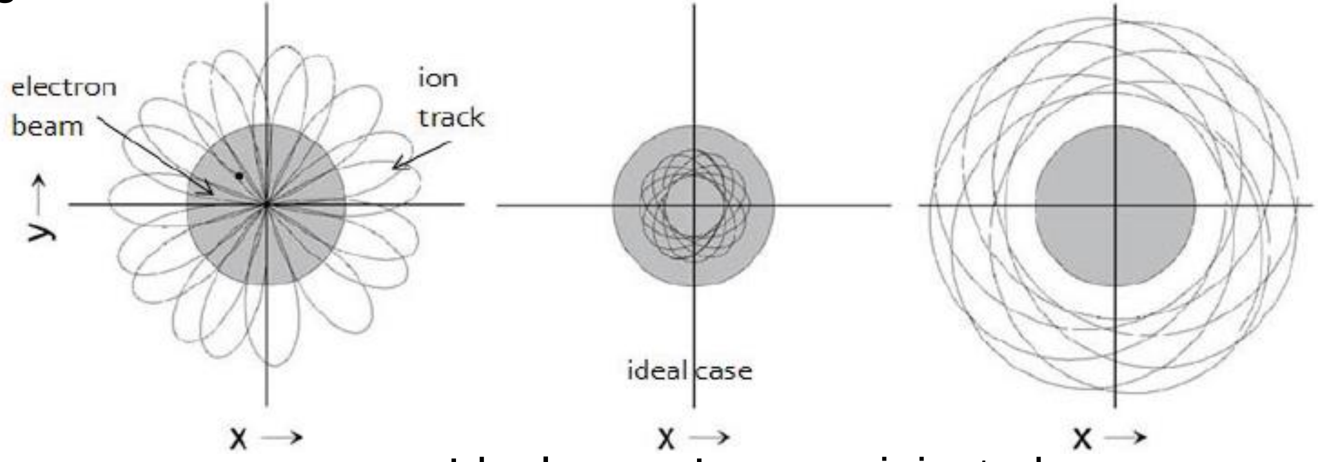
Currell, F. and G. Fussmann, *Physics of Electron Beam Ion Traps and Sources.* IEEE Transactions on plasma science, 2005. **33**(6).

Overlap function for ions injected into the EBIT can be tricky

- If an external beam is injected into the EBIT(as 1+ or 2+ beam) the alignment of the beam in respect to the electron cloud is critical
- If the ions are spending part of the time outside of the e-beam the effective electron density will be reduced

Partial overlap ions are cycling through the electron cloud

No interaction of the ions with the electron beam



Ideal case: Ions are injected into the electron cloud

Wenander, F.J.C., *Charge Breeding of Radioactive Ions*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Overlap function for ions injected into the EBIT

- If the beam is injected from the outside (as 1+ or 2+ beam) the alignment of the beam in respect to the electron cloud is critical
- If the ions are spending part of the time outside of the e-beam the effective electron density will be reduced
- Can define an EBIS acceptance

e beam radius

$$\alpha_{\max} = x_{\mathrm{outmax}} x'_{\mathrm{outmax}} \pi = \pi \frac{r_{ebeam}}{\sqrt{2U_{ext}}} \cdot \left(B r_{ebeam} \sqrt{\frac{q}{m}} + \sqrt{\frac{q B^2 r_{ebeam}^2}{4m} + \frac{\rho_l}{2\pi\varepsilon_0}} \right)$$

Ion Injection Potential

Magnetic field
(focusing of ions)

Electron Space Charge
(Trapping Potential)

$\rho_l = \frac{I}{v_e}$ ....$charge/meter$

r_{ebeam} ....$e\,beam\,radius$

Wenander: RexEBIT http://cds.cern.ch/record/478399/files/open-2000-320.pdf?version=1

Ionization Balance in the EBIT Trap

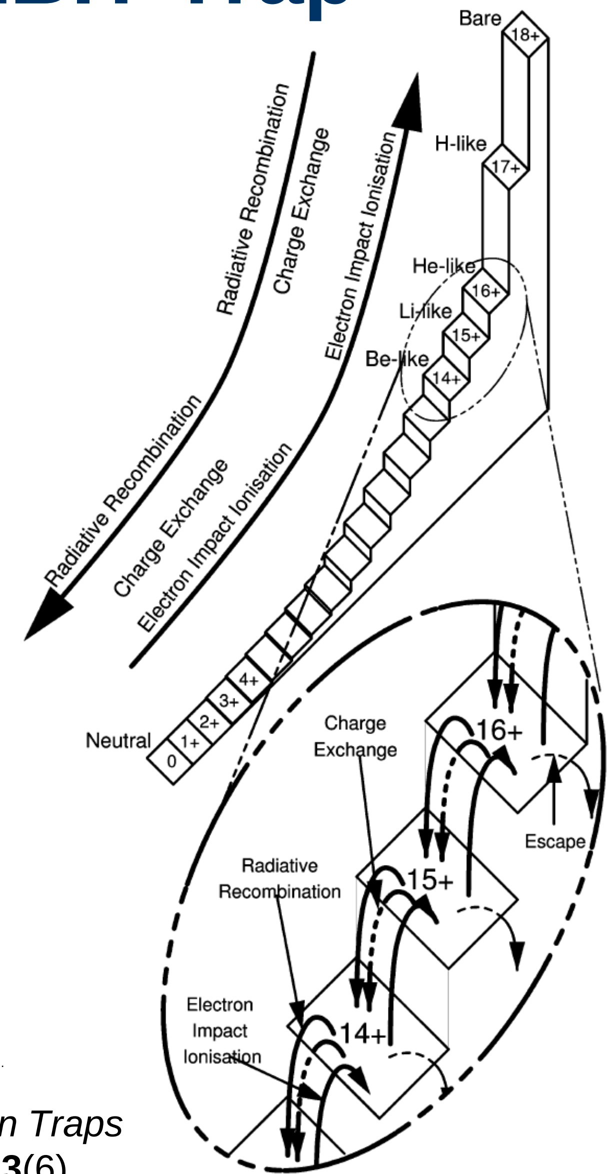
- Ionization through electron impact (step-by-step) until charge state balance is reached

  Charge generation processes x charge destructive processes

  Main Atomic processes are

  1. Electron Impact Ionization
  2. Charge Exchange
  3. Radiative Recombination

- Multiple collisions are required – the ionization time must be long enough to reach desired charge state
- Losses must be controlled to allow reaching the desired charge state
- Vacuum level must be controlled to minimize charge exchange and trap loading by residual gas



*__Currell, F. and G. Fussmann__, *Physics of Electron Beam Ion Traps and Sources.* IEEE Transactions on plasma science, 2005. **33**(6).

Charge evolution – ionization balance

The charge evolution can be described through a set of coupled differential equations

$$\frac{dN_i}{dt} = \boxed{\frac{J_e}{e} \cdot (N_{i-1} \cdot \sigma_{i-1}^{EI} \cdot f_{e,i-1} - N_i \cdot \sigma_i^{EI} \cdot f_{e,i})}$$
$$+ \boxed{\frac{J_e}{e} \cdot (N_{i+1} \cdot \sigma_{i+1}^{RR} \cdot f_{e,i+1} - N_i \cdot \sigma_i^{RR} \cdot f_{e,i})}$$
$$+ \boxed{n_0 \cdot (N_{i+1} \cdot < \sigma_{i+1}^{CX} \cdot v > \cdot f_{e,i-1} - N_i \cdot < \sigma_i^{CX} \cdot v >)}$$
$$- \boxed{(N_i \cdot R_i^{Esc})}$$

EI … Electron Impact Ionization

RR … Radiative Recombination

CX … Charge Exchange

R_i^{Esc} … *Rate of Ion Loss*

For a single species:
2(i+1) coupled differential equations!

i+1 charge dynamics
i+1 energy dynamics

Realistic simulation models are complex - but general guideline for performance can be derived by simplified estimates and upper limits

Electron Impact Ionization

$$X^{q+} + e^- \rightarrow X^{(q+1)+} + 2e^-$$

$$\boxed{\frac{J_e}{e} \cdot \left(N_{i-1} \cdot \sigma_{i-1}^{EI} \cdot f_{e,i-1} - N_i \cdot \sigma_i^{EI} \cdot f_{e,i}\right)}$$

Ionization Potentials

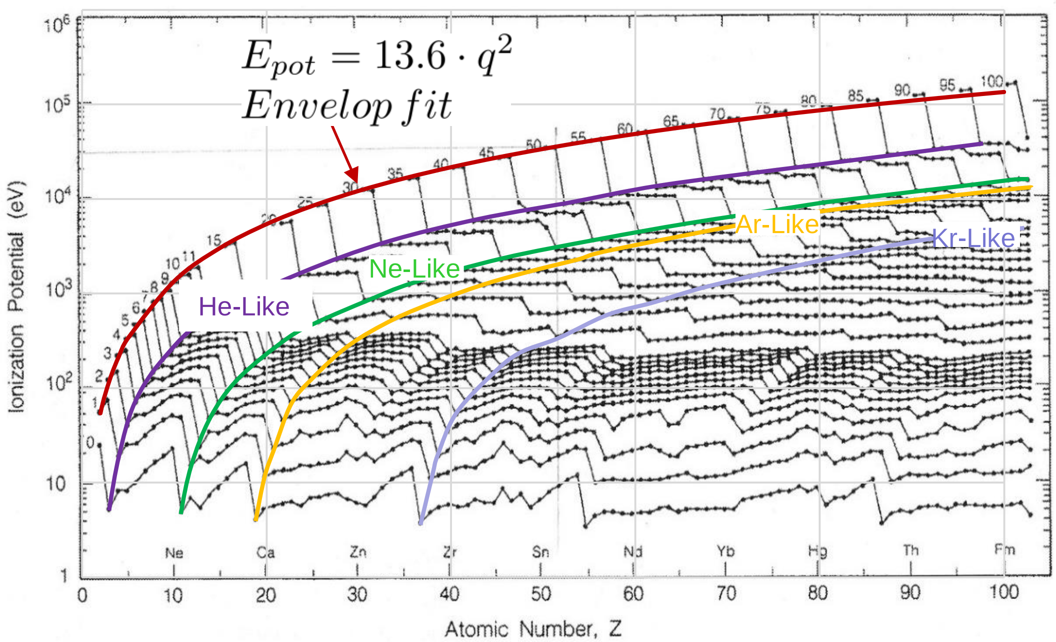
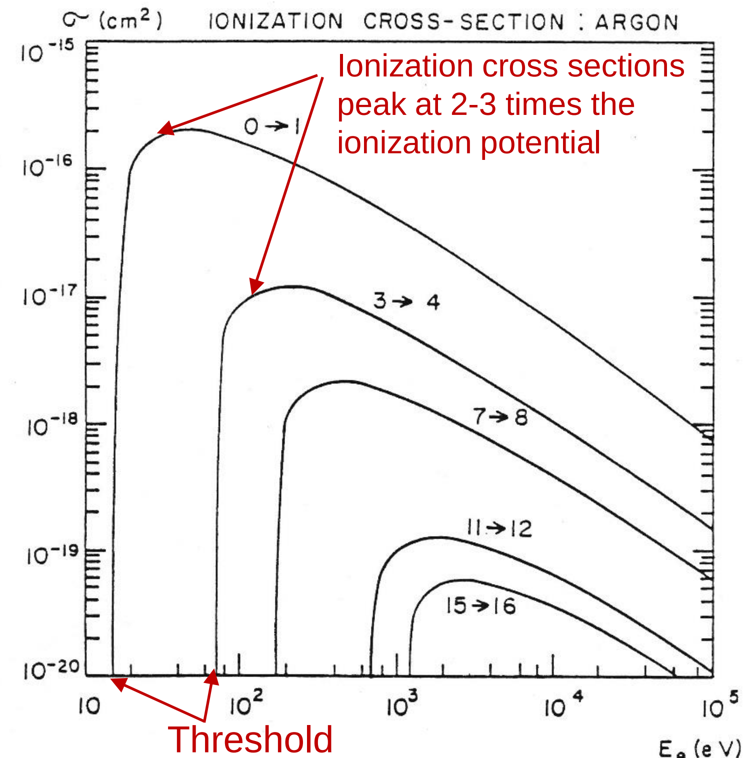


Figure 2.3 Ionization potentials for multiply charged ions of all of the elements [15].



A. Müller, E. Salzborn, R. Frodi, R. Becker, H. Klein, and H. Winter, J. Phys., 1980. B 13: p. 1877. XBL 8611-4404

$$\sigma_{i,i+1} = 1.4 \cdot 10^{-13} \frac{ln \frac{E_e}{E_i}}{E_e E_i} (eV)^2 cm^2$$

E_e: E-beam energy

E_i: Ionization potential

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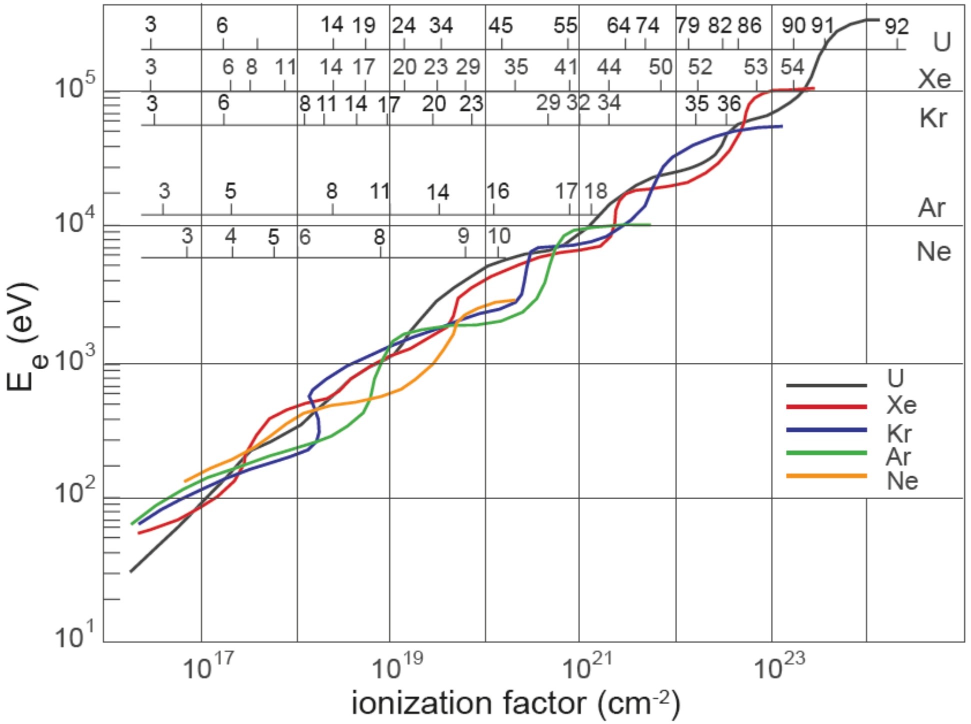
Ionization Factor: Product of the electron flux and the time of bombardment

Probability for Ionization:

$$P_{q \to q+1} = \sigma_{q \to q+1} \cdot j_e \cdot \tau_i \to 1$$



$$j_e \cdot \tau_q > \sum_{k=1}^{q} \frac{e}{\sigma_k^{EI}}$$

$$with\, j_e = v_e \cdot n_e \cdot e \ldots electron\, beam\, density$$

jτ: quality factor/ tuning factor for an EBIT ion source is the combination of the electron density (electron gun current + compression)
Depending on the ionization potential of the desired charge state and electron beam density, the minimum confinement time can be calculated

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Ideal production conditions for ions of different isoelectronic sequences.

$$example\ electron\ beam\ 150\,mA,\ r = 30\mu m,\ j_e = 5.3 \cdot 10^3 \frac{A}{cm^2}$$

Sequence	Neon $Z = 10$	Argon $Z = 18$	Krypton $Z = 36$	Xenon $Z = 54$	Gold $Z = 79$	Uranium $Z = 92$
Atom fully ionized	Ne^{10+} 2×10^{21} 3 7 ms	Ar^{18+} 2×10^{21} 9 67 ms	Kr^{36+} 3×10^{22} 40 1 s	Xe^{54+} 2×10^{23} 80 7 s	Au^{79+} 6×10^{23} 180 20 s	U^{92+} $2 \times 10^{24+}$ 300 67 s
Helium- like	Ne^{8+} 8×10^{18} 0.6 0.3 ms	Ar^{16+} 1×10^{20} 2 3 ms	Kr^{34+} 2×10^{21} 7 67 ms	Xe^{52+} 2×10^{22} 20 0.7 s	Au^{77+} 6×10^{22} 45 2 s	U^{90+} 2×10^{23} 70 7 s
Neon- like		Ar^{8+} 3×10^{18} 0.3 0.1 ms	Kr^{28+} 3×10^{20} 4 10 ms	Xe^{44+} 2×10^{21} 8 67 ms	Au^{69+} 6×10^{21} 17 200 ms	U^{82+} 3×10^{22} 30 1 s
Argon- like			Kr^{18+} 1×10^{19} 1.5 0.3 ms	Xe^{36+} 2×10^{20} 5 7 ms	Au^{61+} 1×10^{21} 12 33 ms	U^{74+} 5×10^{21} 20 167 ms
Krypton- like				Xe^{18+} 6×10^{18} 1 0.4 ms	Au^{43+} 1×10^{20} 4 3 ms	U^{56+} 7×10^{20} 7 23 ms
Xenon- like					Au^{25+} 2×10^{19} 1.5 0.7 ms	U^{38+} 7×10^{19} 4 2 ms

Optimum Electron Energy
Confinement Time Required

arXiv:1411.2445 ; CERN-2013-007
G.Zschornack, et.al

Key Concepts

- Residual gas pressure
- Compensation
- Pulsed operations

Maximum Capacity of the trap

How many particles can be stored?

$$C_{el} = \frac{1}{e}\sqrt{\frac{m_e}{2 \cdot Ee}} I_e L = \frac{I_e L}{v_e}$$

- How many particles can be extracted in one pulse (upper limit for one charge state)

$$N_q = \frac{I_e L}{v_e q}$$

$$R_q \approx \frac{N_q}{\tau_q} \quad with \quad j_e \cdot \tau_q > \sum_{k=1}^{q} \frac{e}{\sigma_k^{EI}}$$

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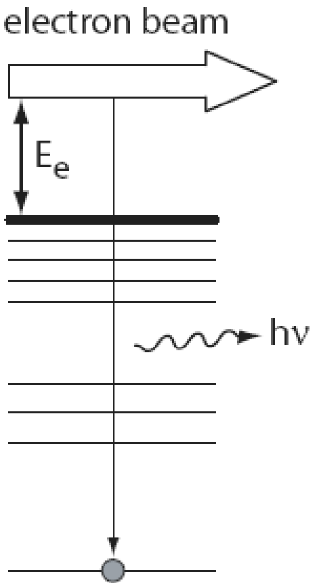
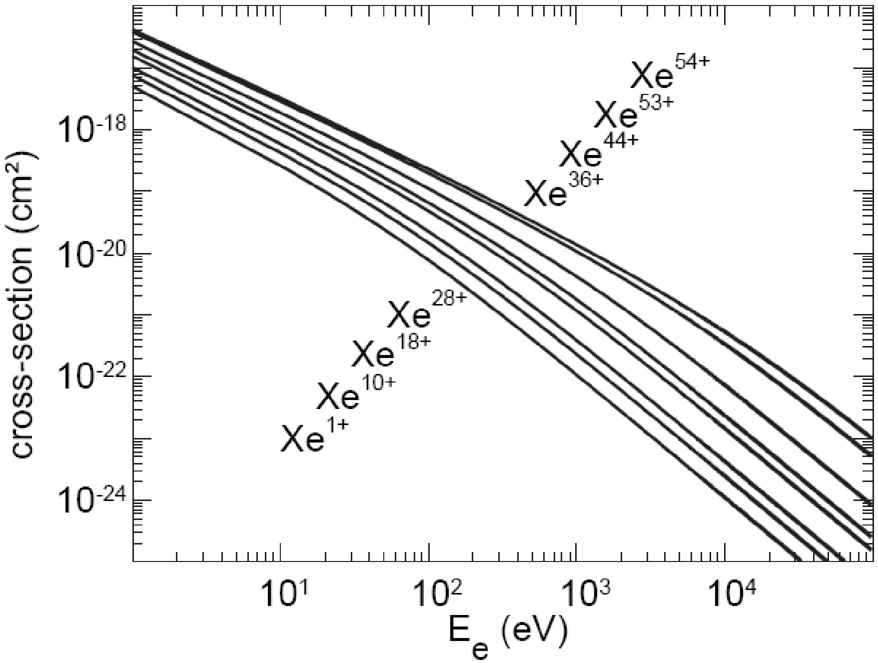
Radiative Recombination Processes

$$\boxed{\frac{J_e}{e} \cdot \left(N_{i+1} \cdot \sigma_{i+1}^{RR} \cdot f_{e,i+1} - N_i \cdot \sigma_i^{RR} \cdot f_{e,i}\right)}$$

$$X^{q+} + e^- \rightarrow X^{(q-1)+} + h\omega$$

This cross section decreases with increasing electron energy and increases with charge state





$$\sigma_{i\rightarrow i-1}^{RR} \sim Q^2$$

G. Zschornack, et.al, *Electron Beam Ion Sources*, in *CAS - CERN Accelerator School, Ion Sources*. 2013, CERN-2013-007.

Charge Exchange

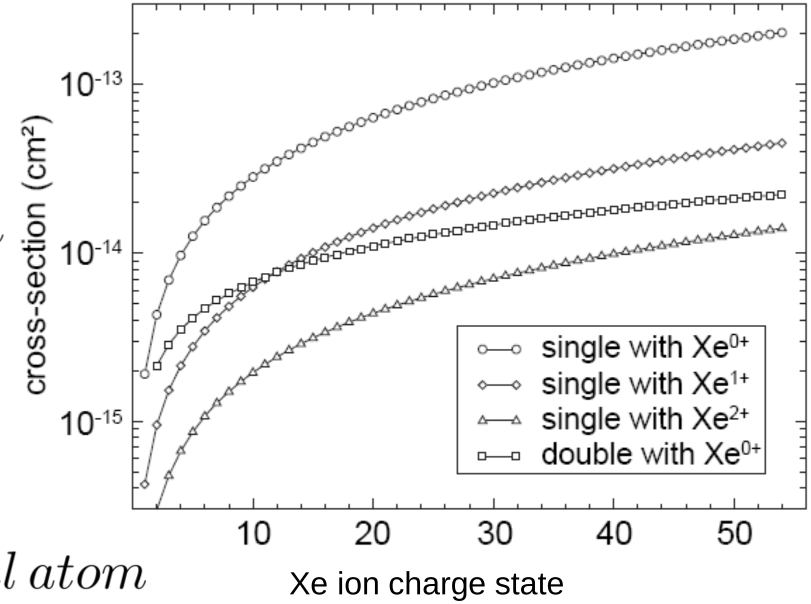
$$\boxed{n_0 \cdot (N_{i+1} \cdot < \sigma_{i+1}^{CX} \cdot v > \cdot f_{e,i-1} - N_i \cdot < \sigma_i^{CX} \cdot v >)}$$

$X^{q+} + X \rightarrow X^{(q-1)+} + X^+$ neutral-ion charge exchange

$n_0 \ldots neutral\, gas\, pressure!$

$v \ldots relative\, velocity$

$\sigma_{i+1}^{CX} \ldots charge\, exchange\, cross\, section$



Increases with Charge State!!

$$\sigma^{CX} = 1.43 \cdot 10^{-12} \cdot q^{1.17} \cdot E_i^{-2.76}$$

$E_i \ldots Ionization\, potential\, of\, the\, neutral\, atom$

$q \ldots Charge\, State$

A. Müller and E. Salzborn, Phys. Lett., 1977. **62A**: p. 391.

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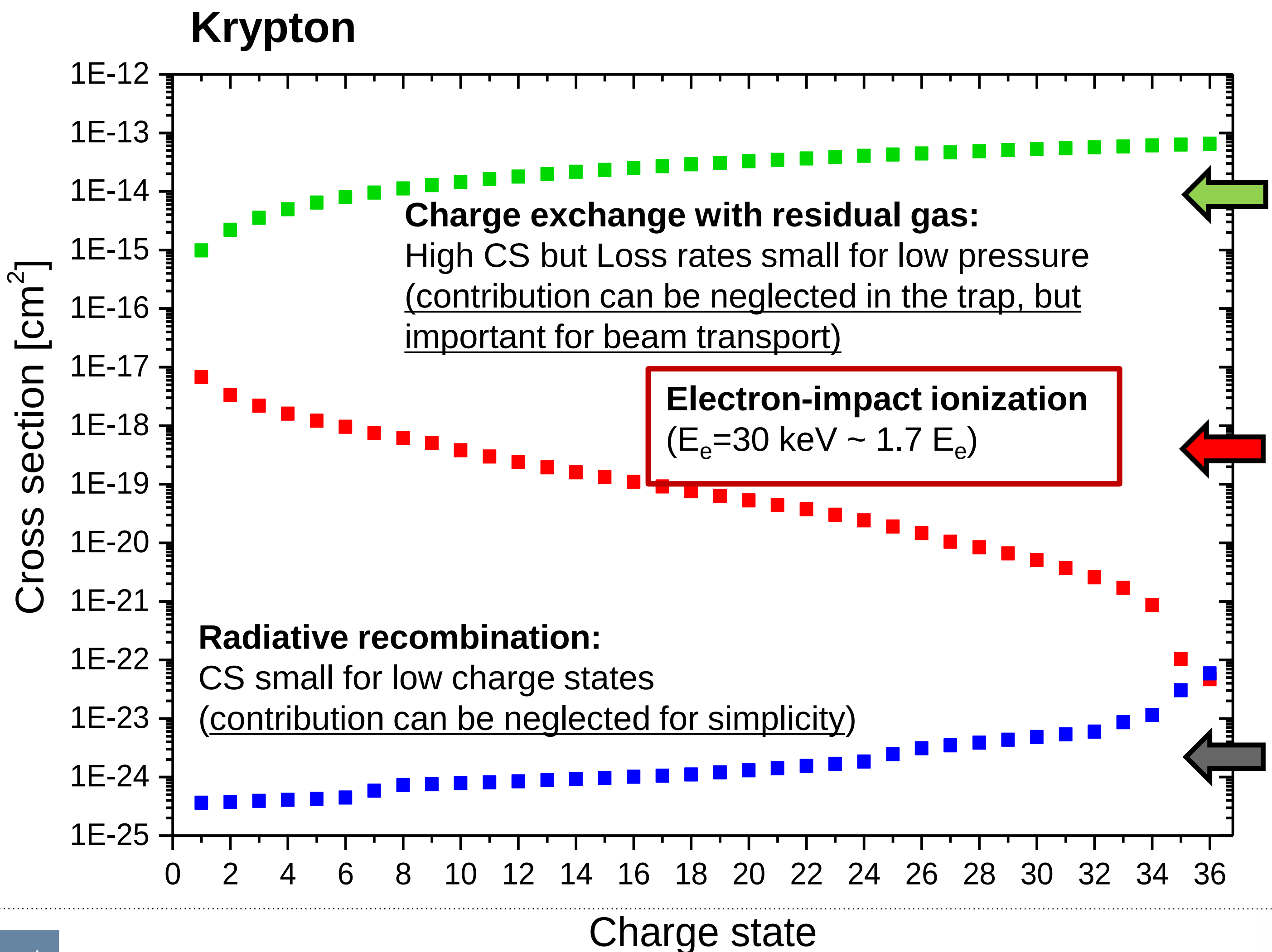
Relative importance of the cross sections in the EBIS



$$\sigma^{CX}_{i\to i-1} \sim Q$$

$$\sigma^{ion}_{i\to i+1} \sim \frac{1}{Q^4}$$

$$\sigma^{RR}_{i\to i-1} \sim Q^2$$

Courtesy: A. Lapierre

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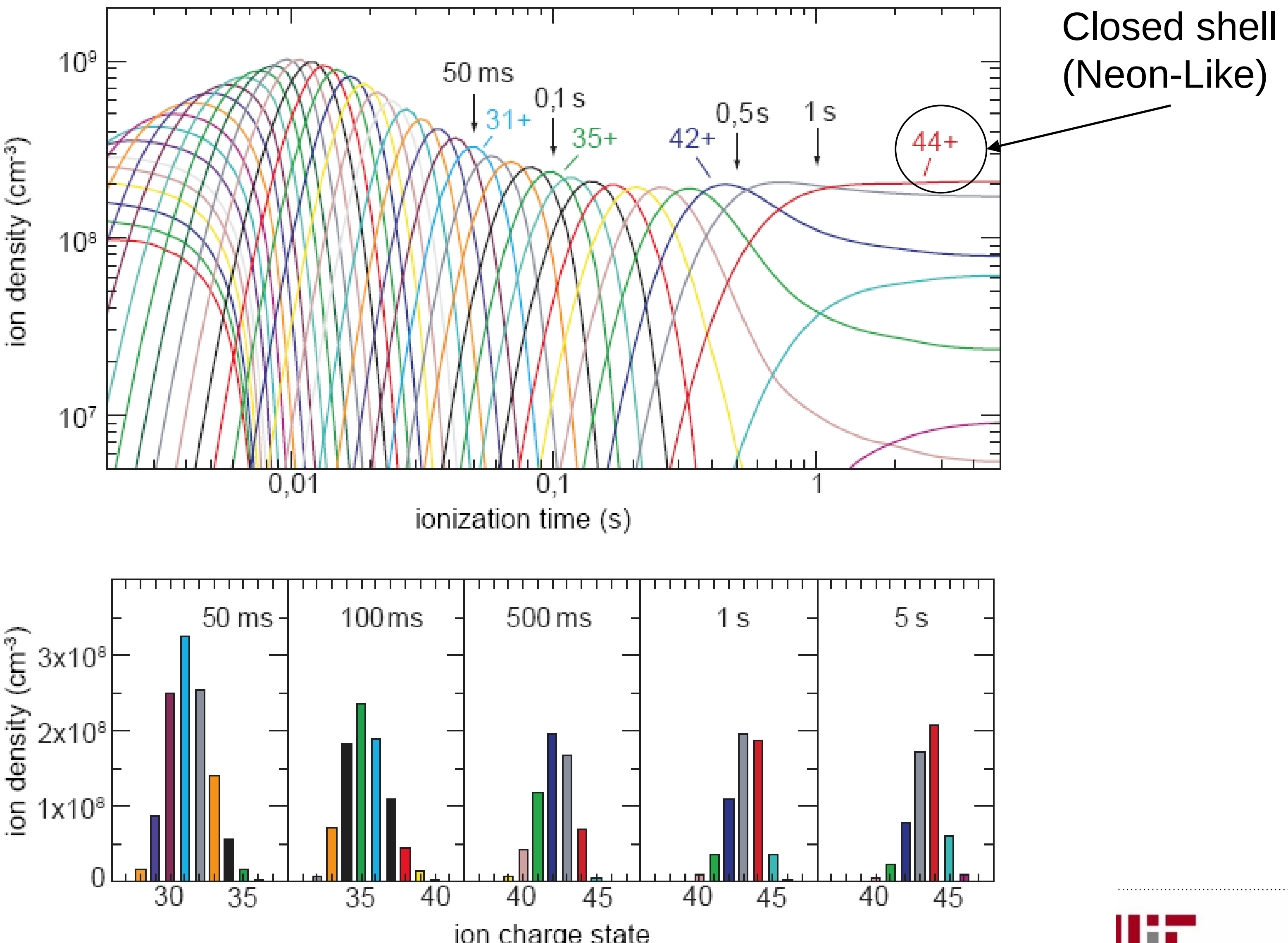
Evolution of the ionization of xenon ions in a Dresden EBIT at E_e = 15 keV, I_e = 40 mA and p =$2\cdot10^{-9}$ mbar.



Ion Losses/Escape from the Trap

- Ion-ion collisions lead rapidly to a Maxwell-Boltzmann distribution (ms)

$$f(E_\mathrm{i}) = \frac{2}{\sqrt{\pi}\,kT_\mathrm{i}}\sqrt{\frac{E_\mathrm{i}}{kT_\mathrm{i}}}\exp\left(-\frac{E_\mathrm{i}}{kT_\mathrm{i}}\right)$$

- The formation of a Boltzmann energy distribution has consequences for the whole ion trap process
  - **Permanent ion losses** At a certain mean ion energy, ions always exist with an energy greater than a critical energy and can leave the trap with the barrier Ub. This means that we have a constant ion loss from the trap: Electron – ion interaction is the main heating source
  - **Evaporative cooling** of multiply charged ions by light low charge state ions. Elastic collisions between ions with different charge states and masses lead to an equilibrium energy distribution for each ion

$$R_i^{Esc} = \frac{3}{\sqrt{2}}\nu_i \frac{e^{-\omega_i}}{\omega_i} \qquad \omega_i = \frac{q_i V_t}{kT_i}$$

Trapping Potential

ion-ion collision frequency: temperature exchange

Ion temperature (heating through electron beam)

EBIS: Energy Dynamics

- **Energy Dynamics** - Processes that change the characteristic temperature of the ions in the trap (kT_i)
  - The hotter the ions the less time they spend in the trap, the less overlap the have with the electron beam
  - Electron beam is a major source of heating through Landau-Sptzer collisions (increases with CS)
  - Ion trapping increases with charge state – higher charge state ions get trapped deeper and can withstand some heating (qeV/kT)
  - Ion-ion collision can be a source of cooling
  - Evaporative cooling: Ions leaving the trap carry energy away from the trap – add lighter gas to the trap or even residual atoms
    Can be used as tuning tool by lowering the extraction trap potential slightly ("leaky" EBIS mode)

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Vacuum in the trap – estimate of trap fill time

$$\sigma_{i,i+1} = 1.4 \cdot 10^{-13} \frac{ln \frac{E_e}{E_i}}{E_e E_i} (eV)^2 cm^2$$

E_e: E-beam energy

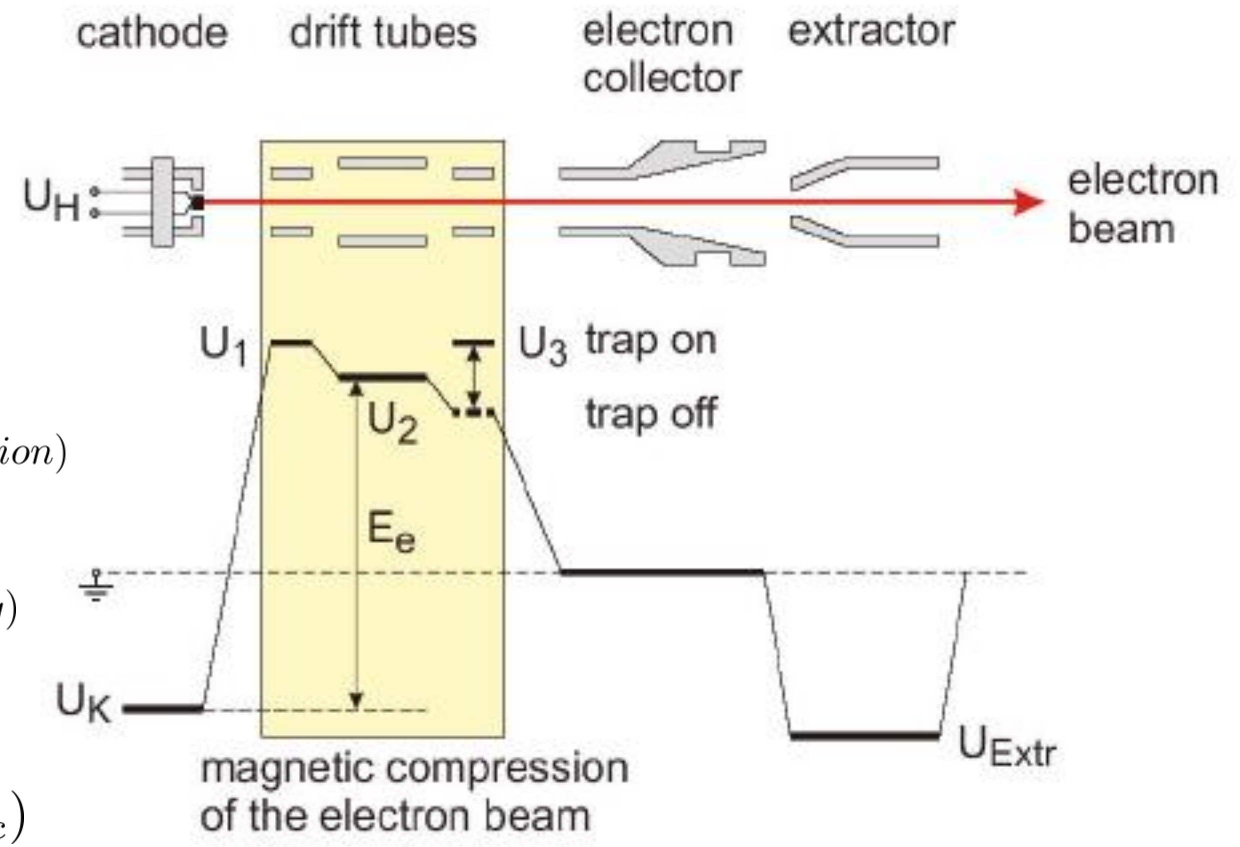
E_i: Ionization potential

$$\tau_{trap} = (\sigma_0 n_0 v_e)^{-1}$$

Time to fill up the trap !
Inverse of the reaction rate of the particles in the trap under the electron beam bombardment !

Homework: Assume the residual gas is nitrogen only, using the Lotz formula and considering only 0→1+ reactions, calculate the time to fill the trap with only residual ions for p=1e-7 mbar, 1e-9mbar, 1e-11mbar, E_e=20 keV

Ion beam extraction



$U_1 ... Trapping\ Potential (e - gun)$

$U_2 ... Middle\ Electrode\ Potential$

$U_3 ... Trapping\ Potential\ (Extraction)$

$U_k ... Cathode Potential (neg)$

$U_{sp} ... Space\ Charge\ Potential (neg)$

$$U_{elec} = e \cdot (U_2 - U_k + U_{sc})$$

$$U_{elec}\ ranges\ from\ 500\ eV\ to\ 200\ keV$$

arXiv:1411.2445 ; CERN-2013-007
G.Zschornack, M.Schmidt and A.Thorn

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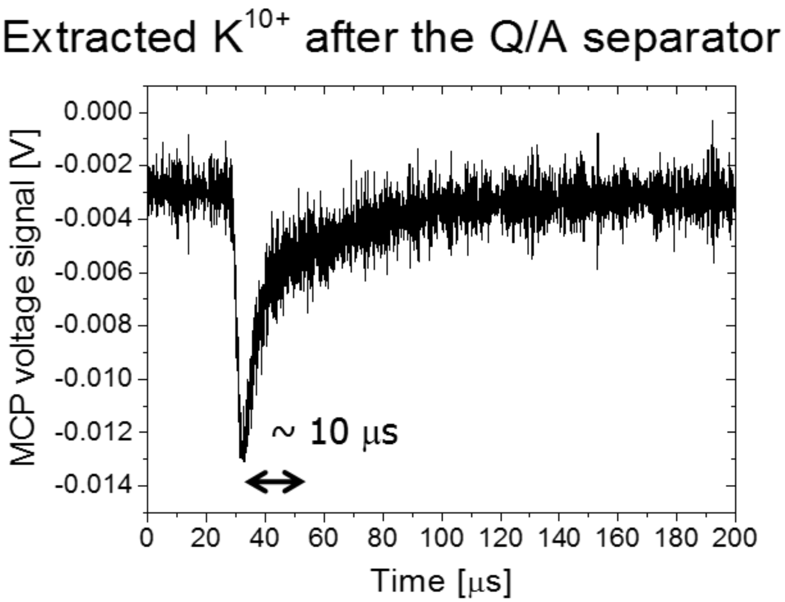
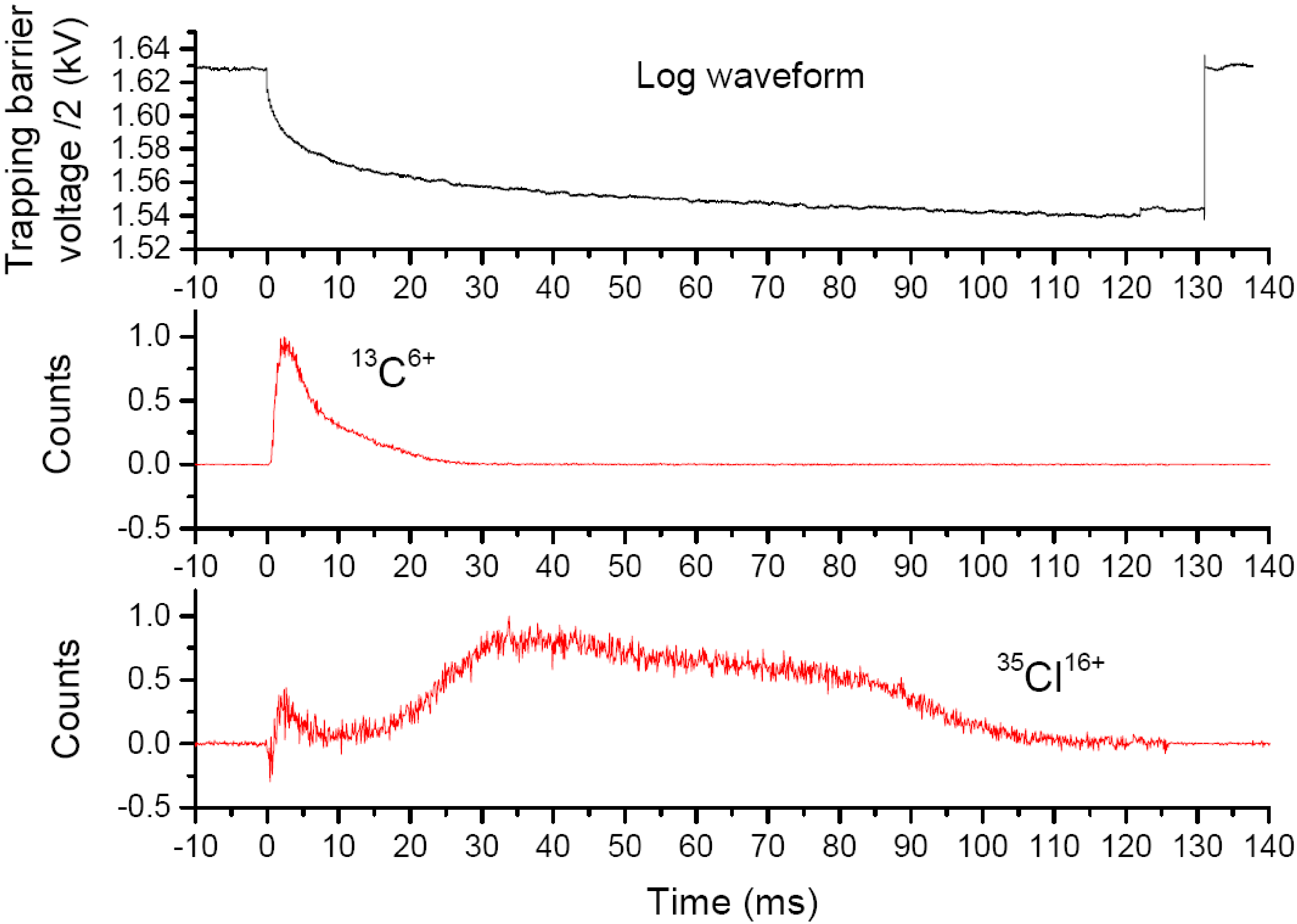
Extraction of Ions from the EBIT

- **Permanently open trap**: Ions are produced without axial trapping (lowest charge states)
- **Partially closed trap** – leaky mode: lower the extraction potential that a certain number of ions can escape – results in low energy spread ions (only the ones that can overcome the remaining trapping potential (low to medium charge state ions, some high charge state – CW operation)
- **Periodically open trap**: pulsed operations, highest current for high charge state ions, $j\tau$ can be controlled!

Pulsed extraction can be timed to achieve the needs of the user

- The problem: Opening the trap releases 10^4-10^9 ions in 10s of microseconds
  - Great for synchrotrons (e.g BNL)
  - Really bad if delivered to users, typical detector rates are Mz or 10^6 particles/sec
  - Therefore the pulse needs to be stretched and the release of ions well controlled
  - Possible by shaping the extraction voltage of the ions to release ions in a rate that is suitable for the end-user
  - Bonus Advantage: results in narrower energy spread ions as the ions are released at nearly the same energy, which leads to better resolution of the mass spectrum in the beam line





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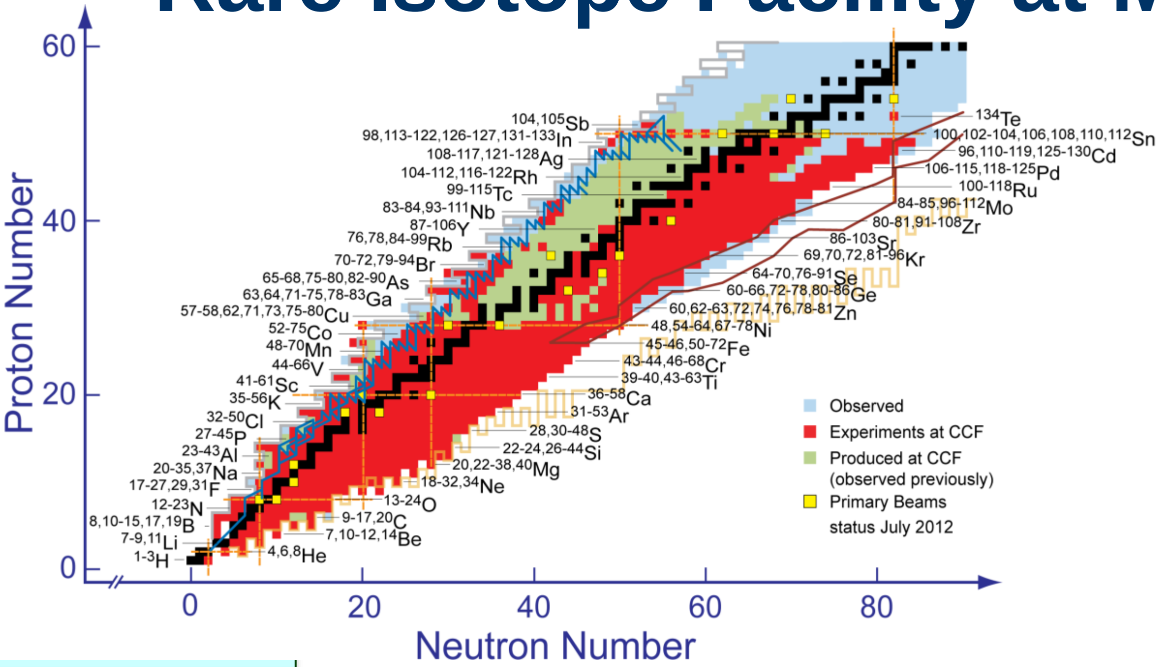
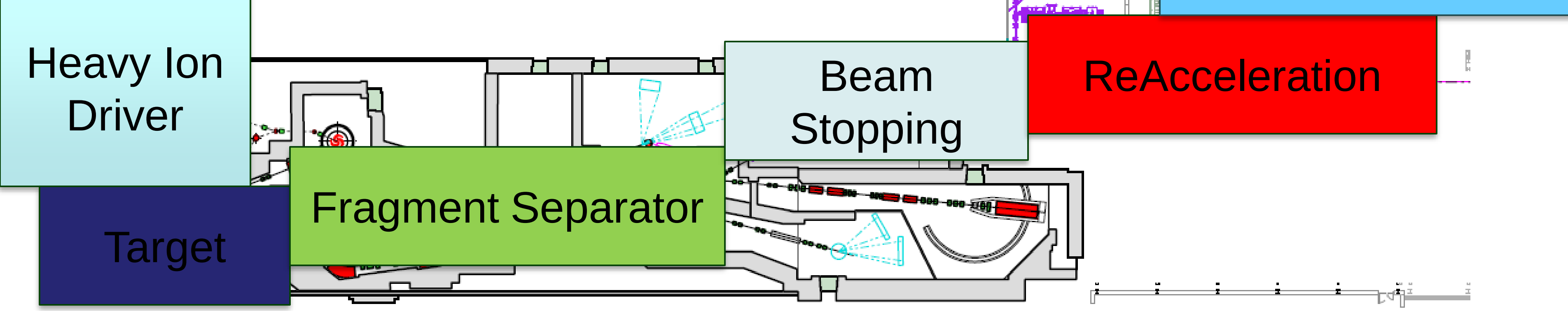
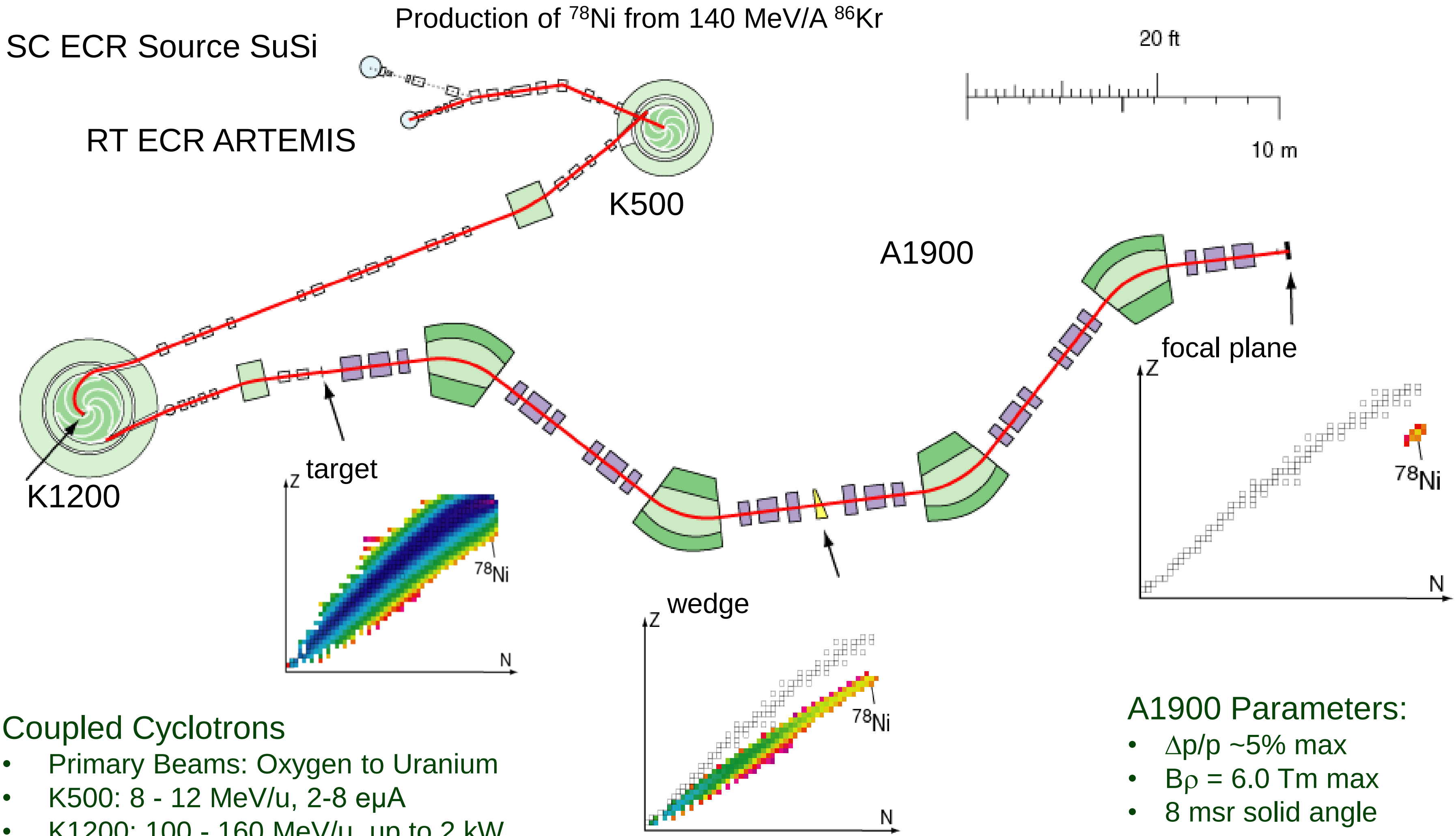
ReAccelerator

Rare Isotope Facility at MSU





Rare Isotope Beam Production



Coupled Cyclotrons

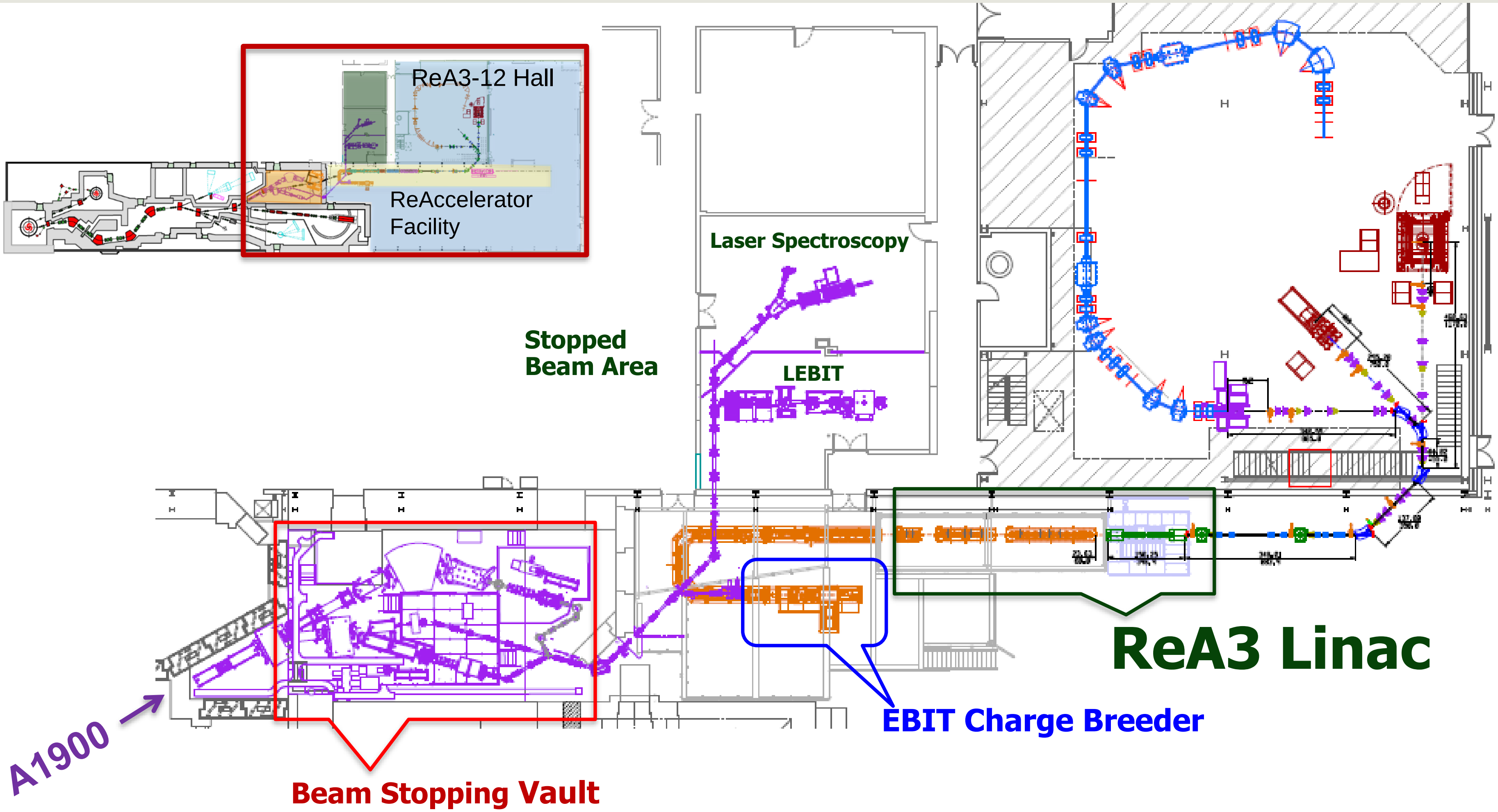
- Primary Beams: Oxygen to Uranium
- K500: 8 - 12 MeV/u, 2-8 eμA
- K1200: 100 - 160 MeV/u, up to 2 kW

A1900 Parameters:

- $\Delta p/p$ ~5% max
- $B\rho$ = 6.0 Tm max
- 8 msr solid angle

Morrissey *et al.*, NIM B 204, 90 (2003)

From Fast To Not-So-Fast



120 MeV/u ~ ½ c → Fully stripped → STOP → 1+ → 60 keV → 1+ → 12 keV/u → n+ → 3 MeV/u

Courtesy of Stefan Schwarz

Deceleration Challenge

Why Not A Linac In Reverse?

- Transverse emittance 💣 + plus momentum spread ~ 5% $\Delta p/p$

Example:

- Emittance for ^{79}Br entering N4:

  ~40 π mm mrad at 6.875 GeV (eq. 3.1Tm)

- Emittance ~ sqrt(E)

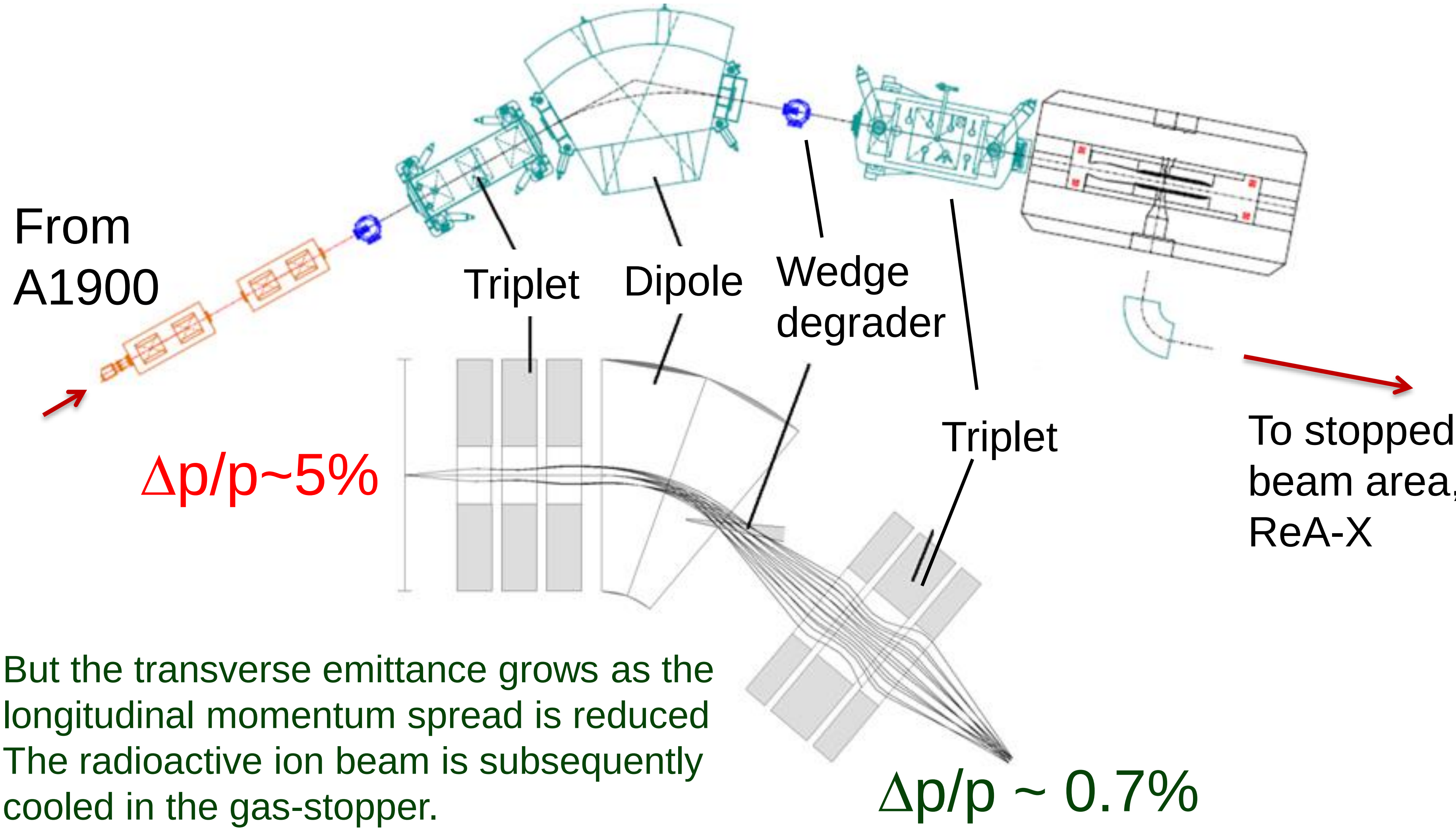
→ at 60 keV (transport in stopped beam area) : 340 π mm mrad

→ at 2 keV (entrance energy into LEBIT/EBIT) : 1854 π mm mrad
(accepts ~40 π mm mrad !)

Solution:

- Momentum compression line for the incoming beam
- Dissipation of energy and cooling in solid/gas followed by extraction with an RF drag field
- Particles "forget" their origin

Momentum Compression Line In The Stopping Vault

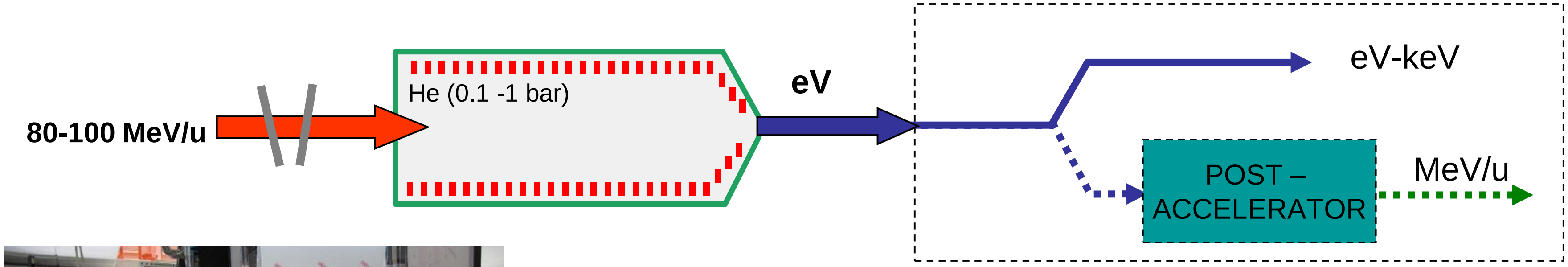


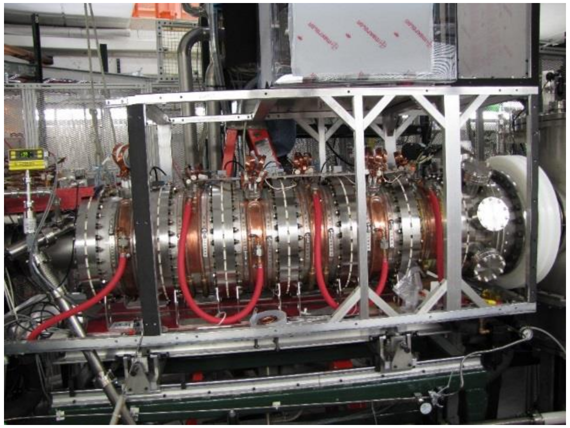
- But the transverse emittance grows as the longitudinal momentum spread is reduced
- The radioactive ion beam is subsequently cooled in the gas-stopper.

Two Gasstopper Systems Are Under Development

ANL Gas Cell Is Installed In The Vault And Commissioned (2013)
Assembly Of The Cyclotron Stopper Is Developed Of Line (2015)

Convert fast-beams produced in projectile fragmentation to low-energy beams:





Linear Gas Stopper

- Concept is proven (ANL, MSU)
- Lots of experience at MSU

Limitations:

- Low efficiency for light ions (stopping range)
- Space charge due to ionization

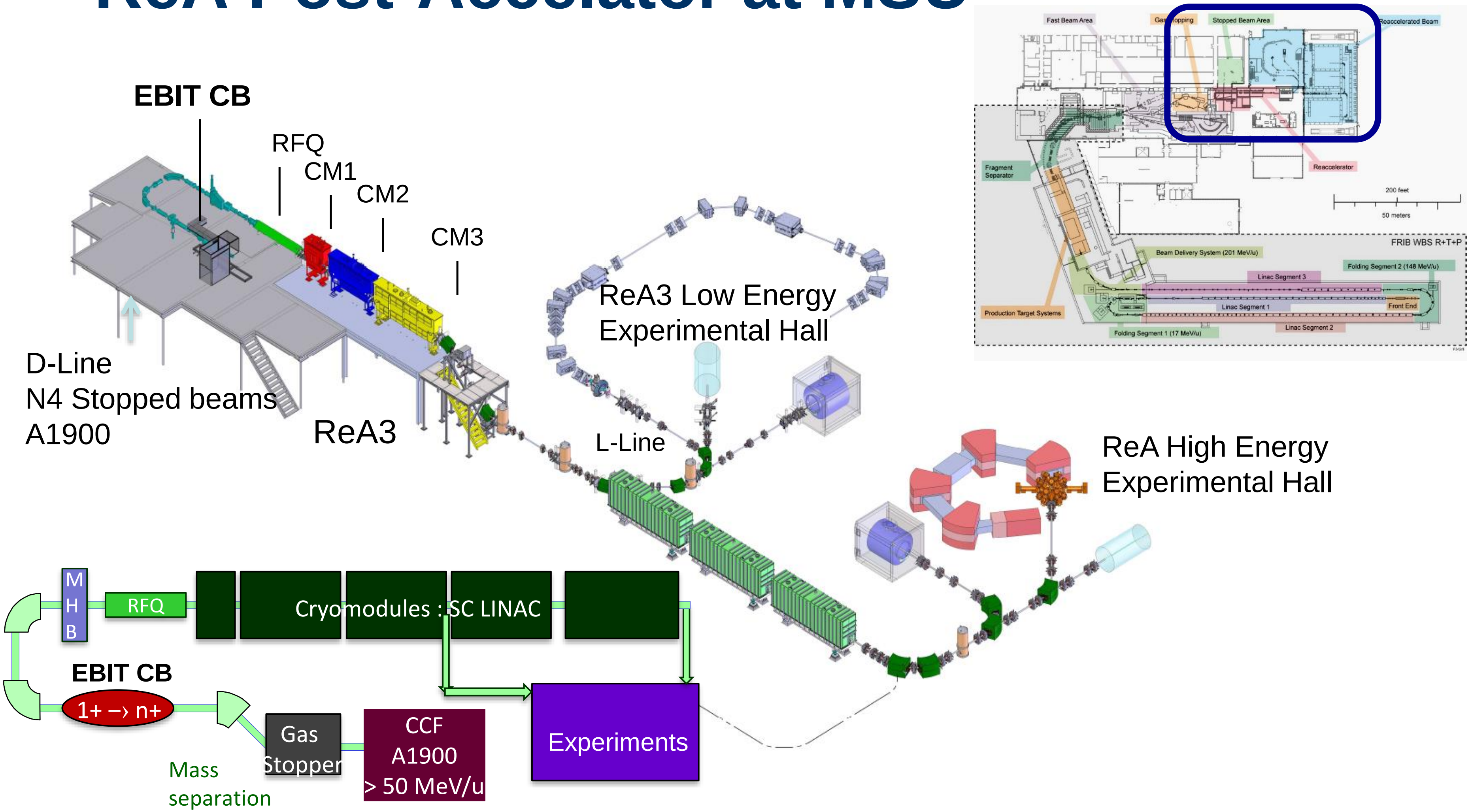
ANL 1.2 m long linear gas cell

High purity helium: ~ 90 Torr, -5^{0}C

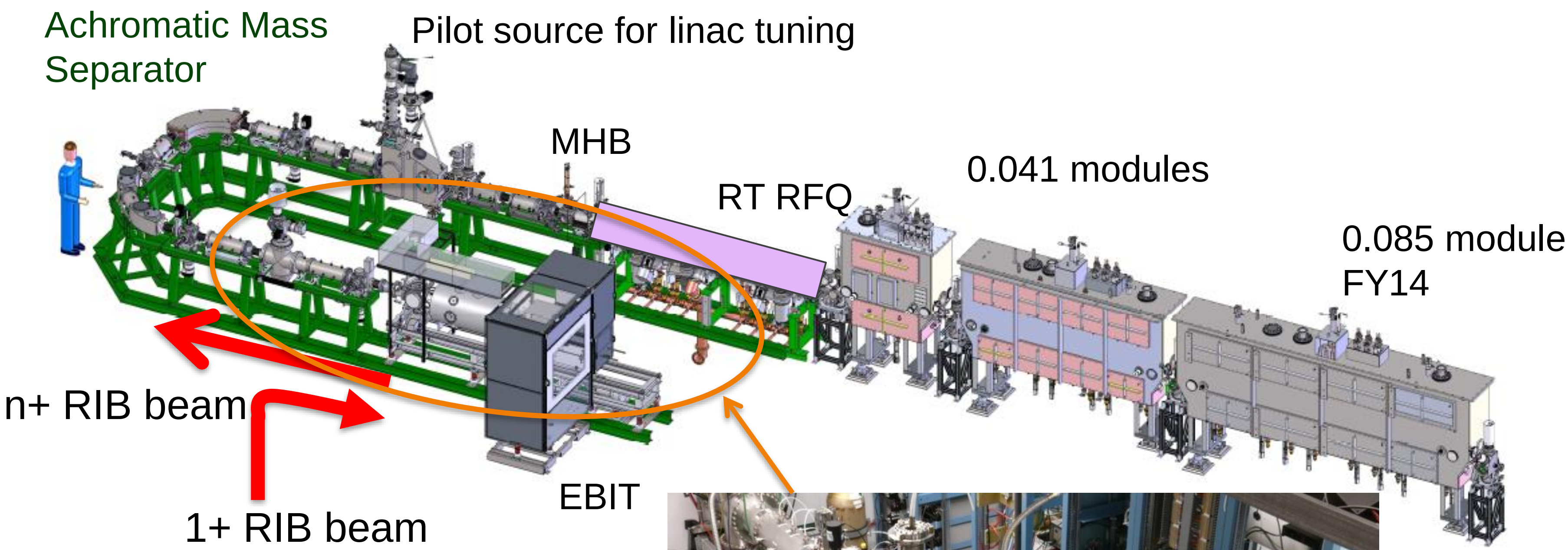
Thermalizes RIB ions to < 1eV

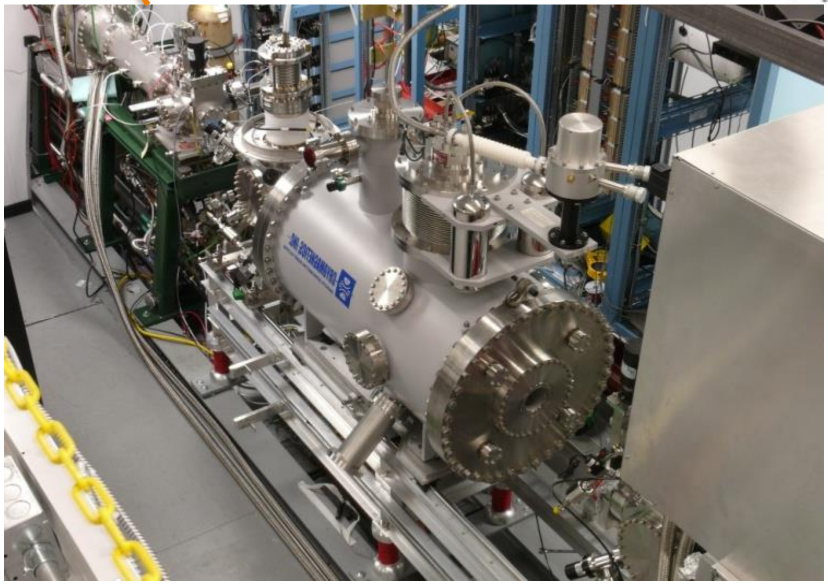
Singly and doubly charged

ReA Post-Accelerator at MSU



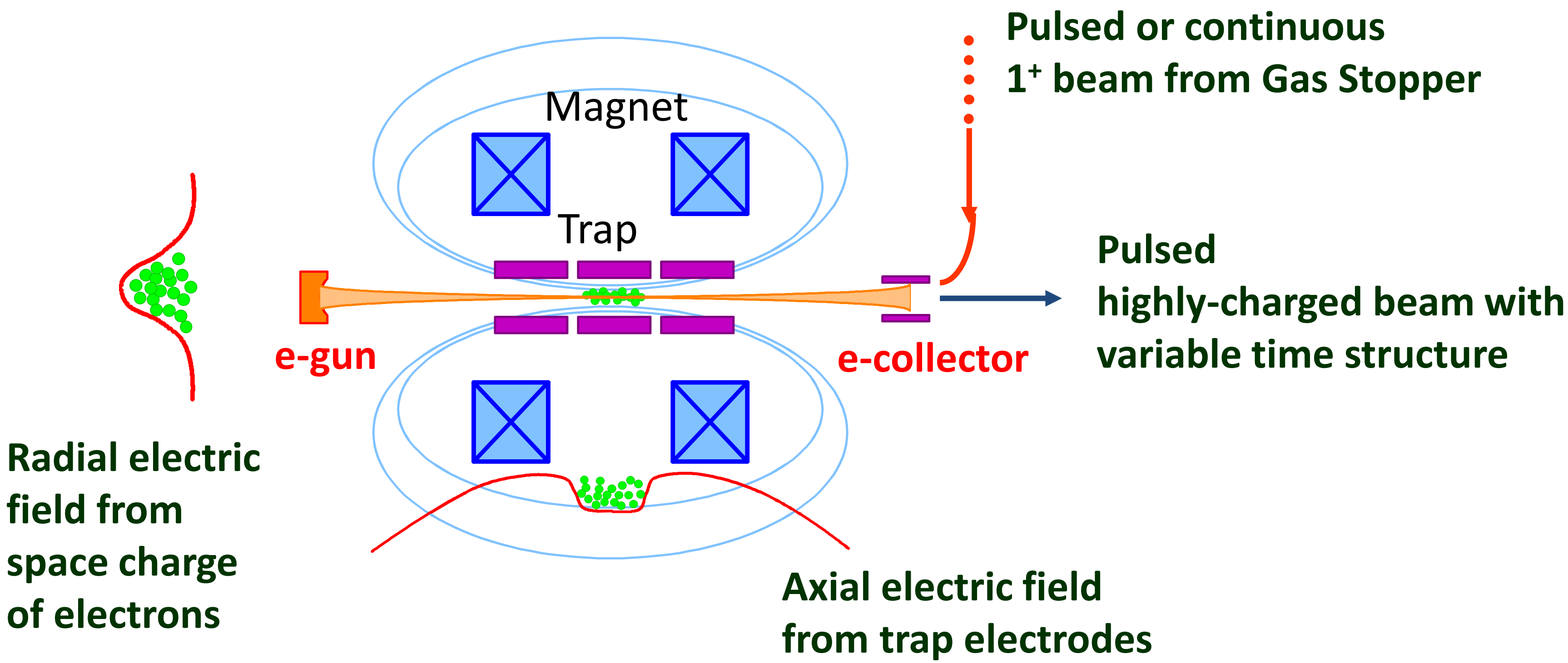
ReA Design Choices: EBIT Charge Breeder



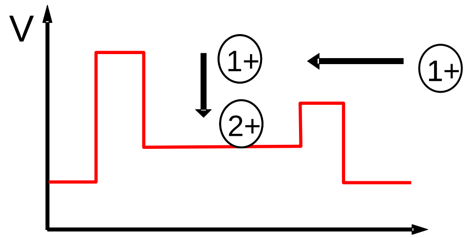


EBIT:
- Short breeding time
- High ionization efficiency
- Charge state flexibility
- Low beam contamination
- $0.5 \leq Q/A \leq 0.2$

Charge Breeding in the EBIT Source

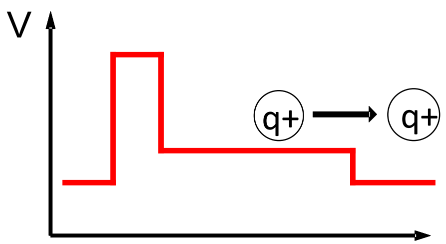


Over-the-potential barrier injection



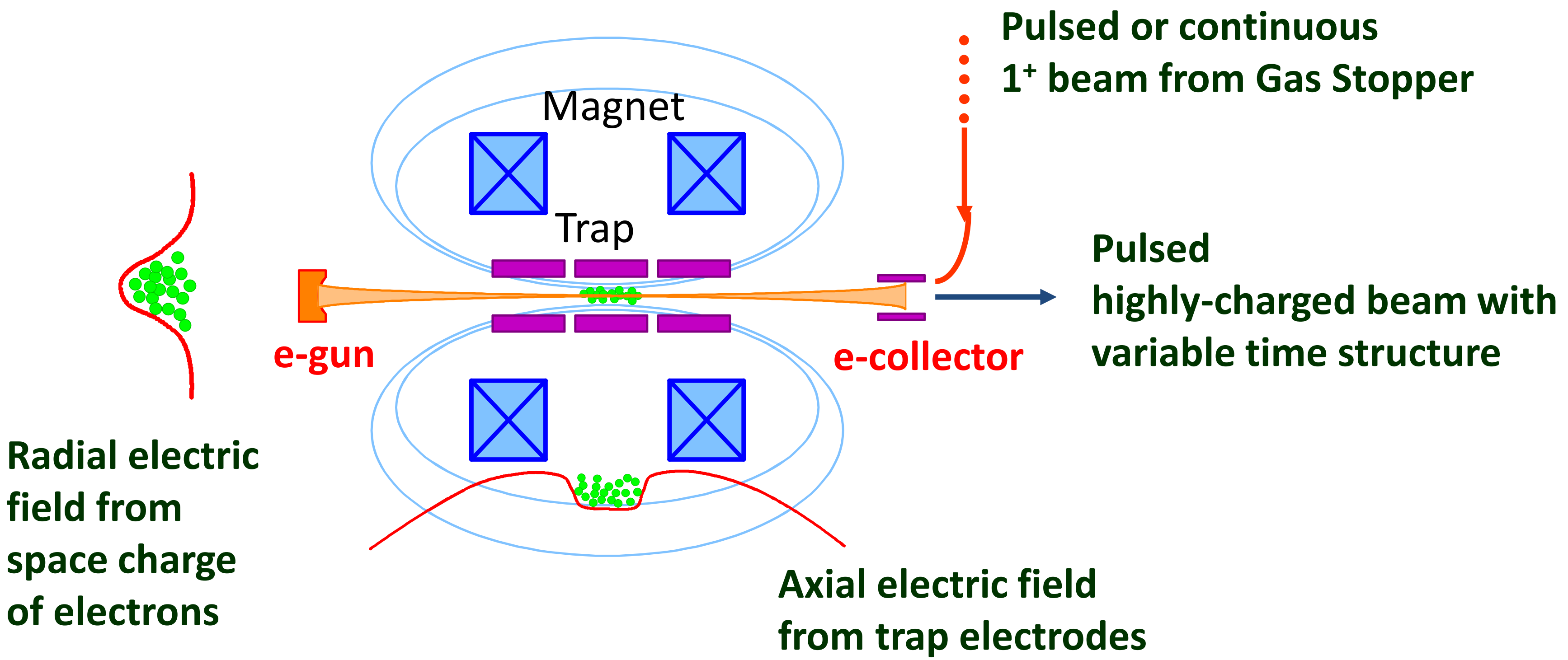
Continuous injection

Lower-the-barrier extraction

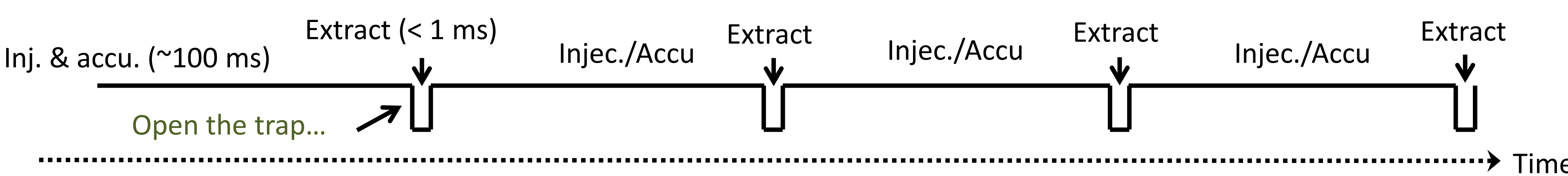


Pulsed extraction

Charge Breeding in the EBIT Source

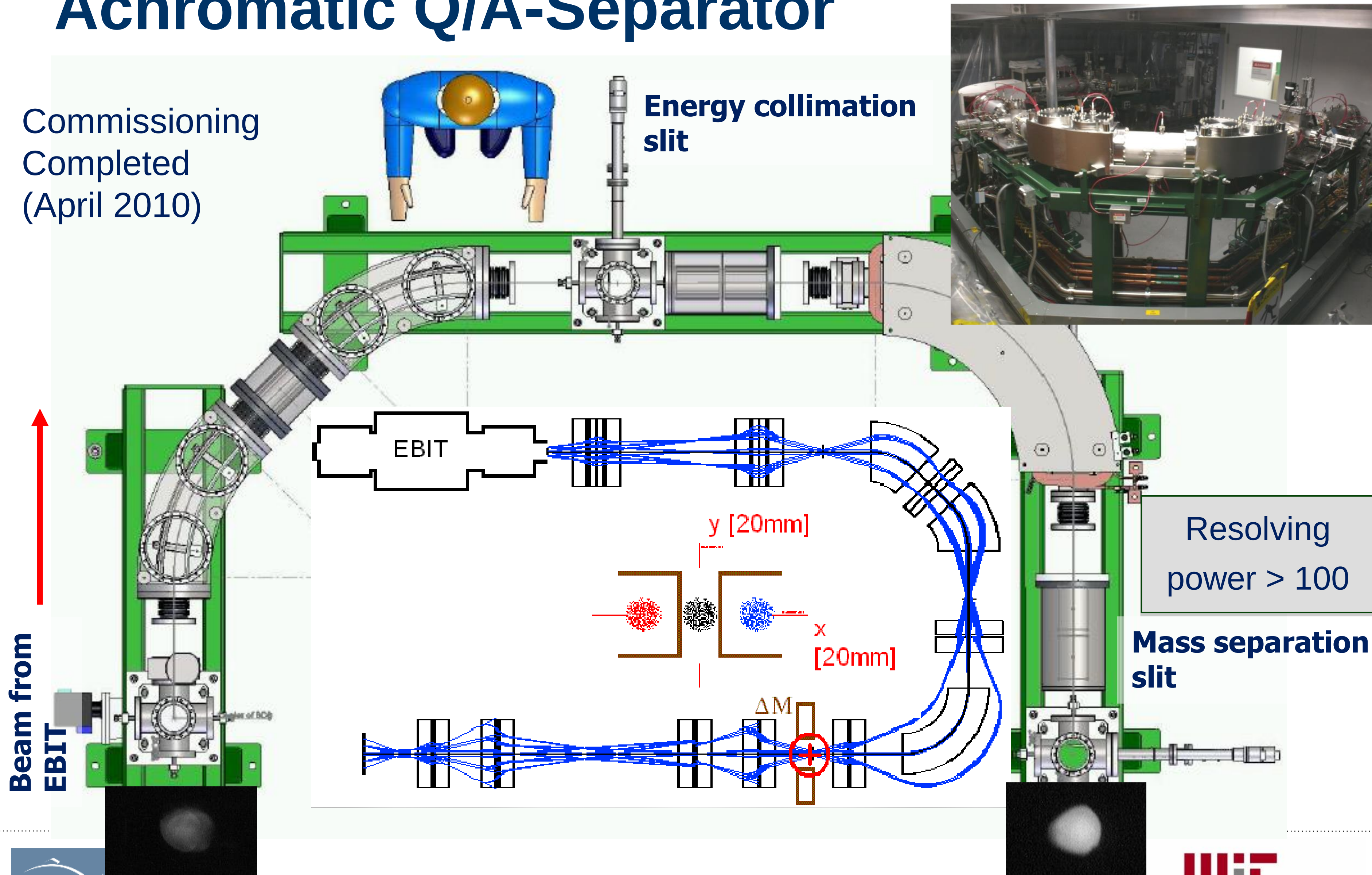


Time sequence



Achromatic Q/A-Separator

Commissioning
Completed
(April 2010)



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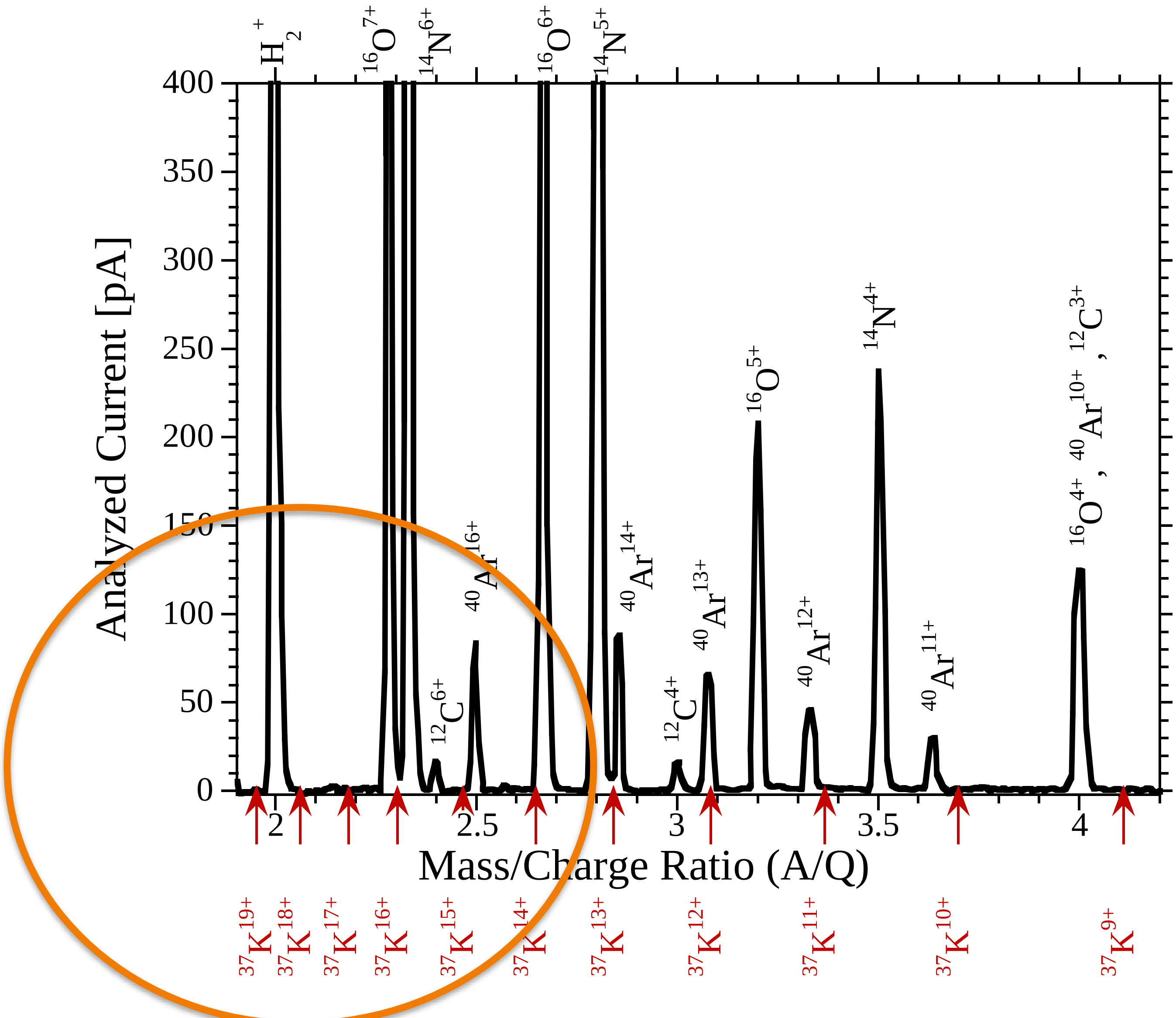
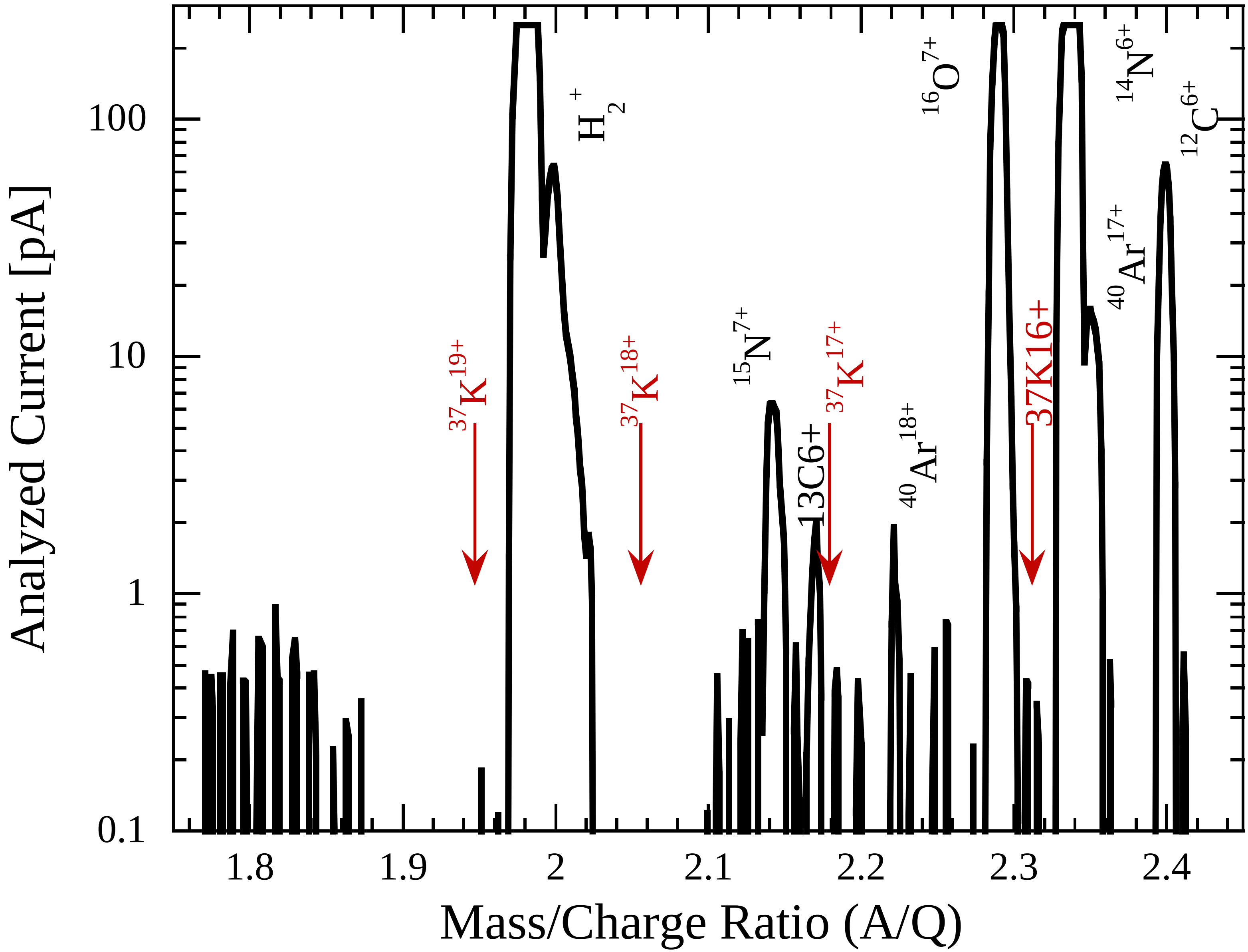
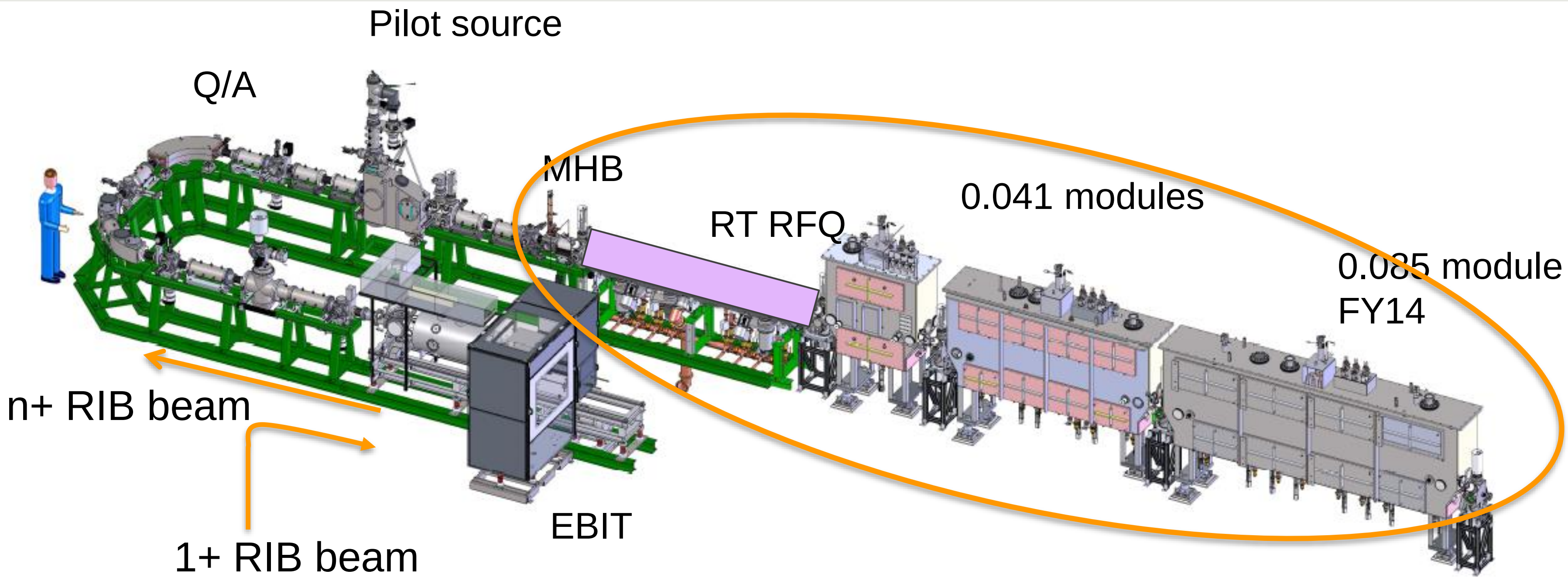
EBIT Background Spectrum And Selection Of ^{37}K Charge States



Background Ions From The Charge Breeder In The Region Of Interest Are Less Than 1 pA



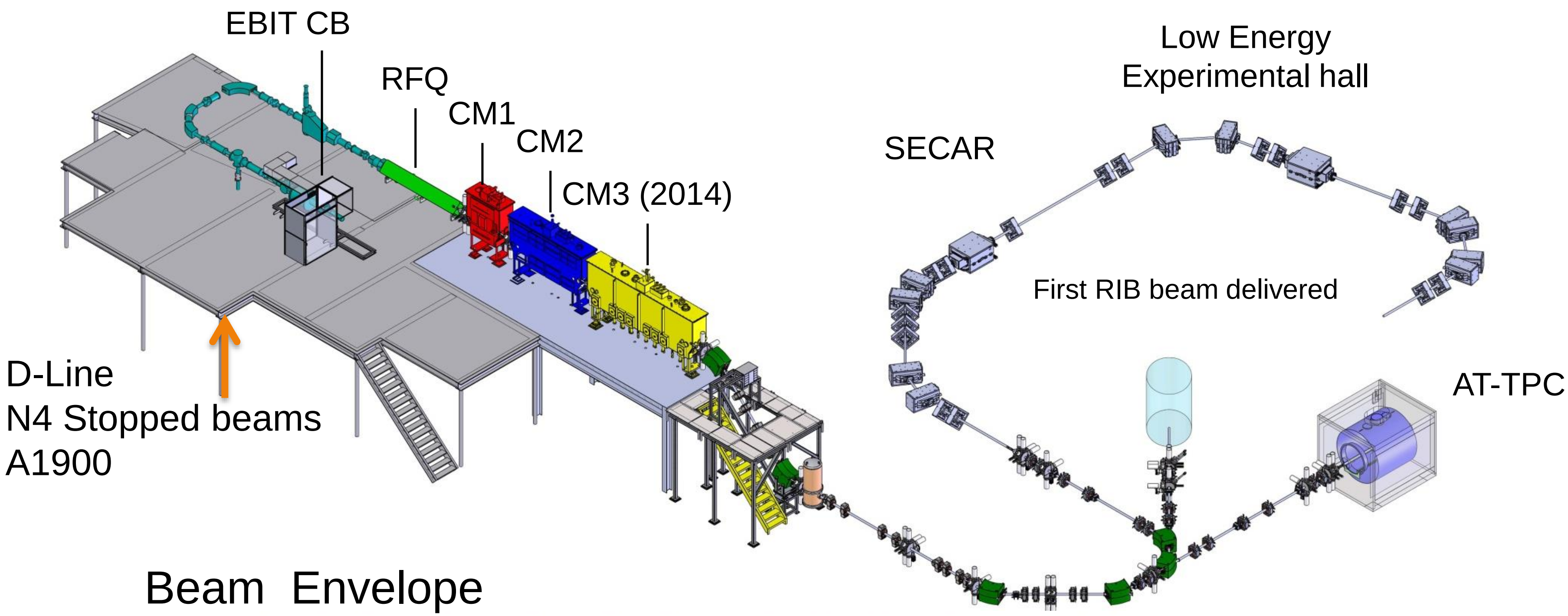
ReA Design Choices: RT-RFQ With External Buncher And High Efficiency SC-Linac



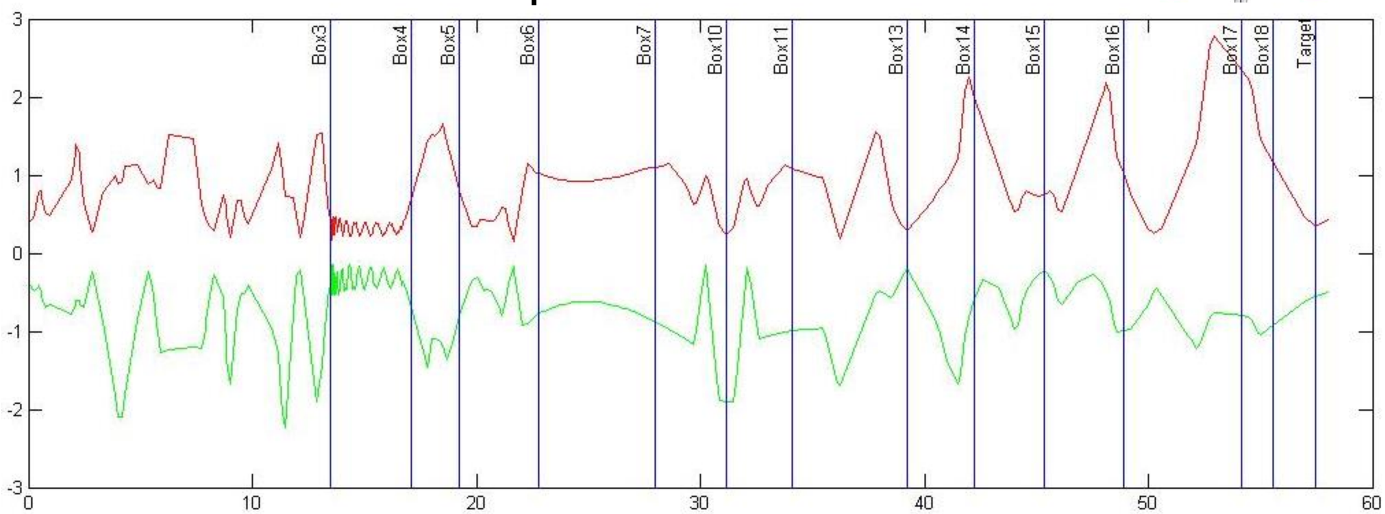
SRF LINAC

- 80.5 MHz RF frequency
- Flexible energy range (from deceleration 300 keV/u to maximum linac energy)

ReA Beamline acceleration and transport to experiments



Beam Envelope



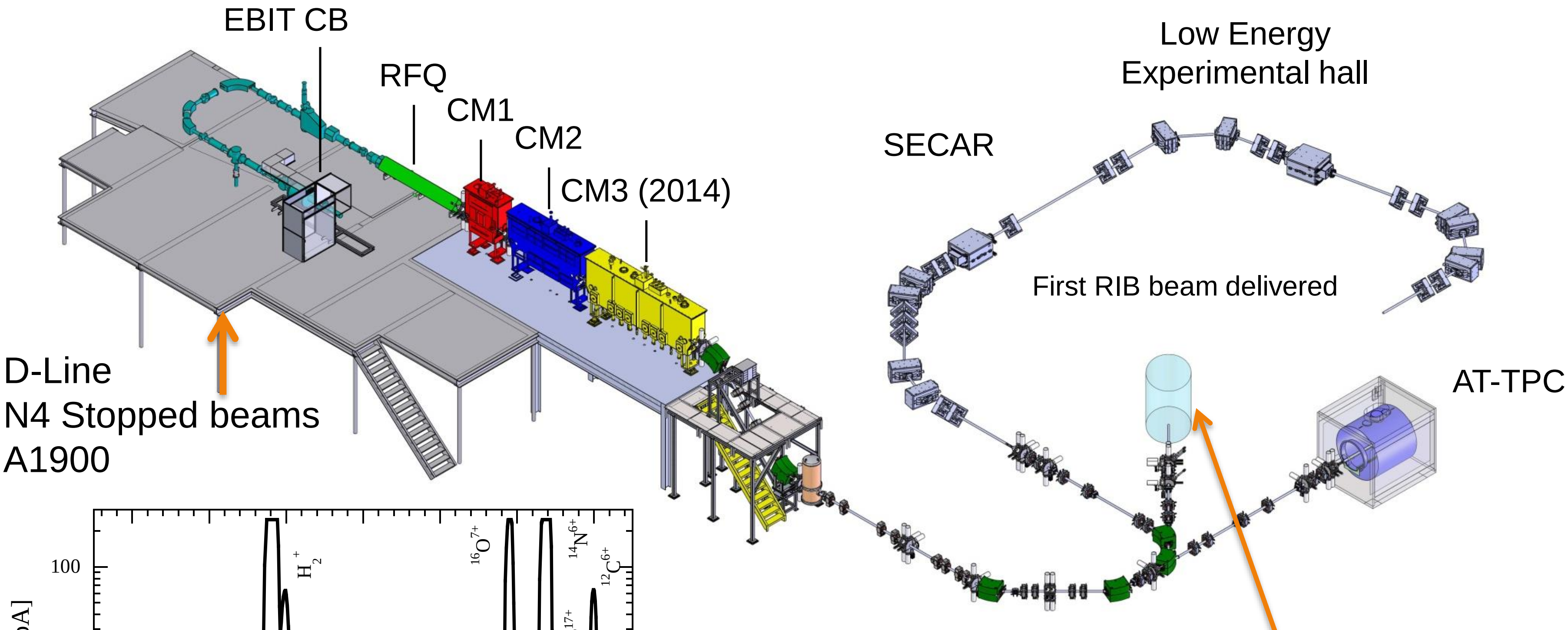
Linac Transmission

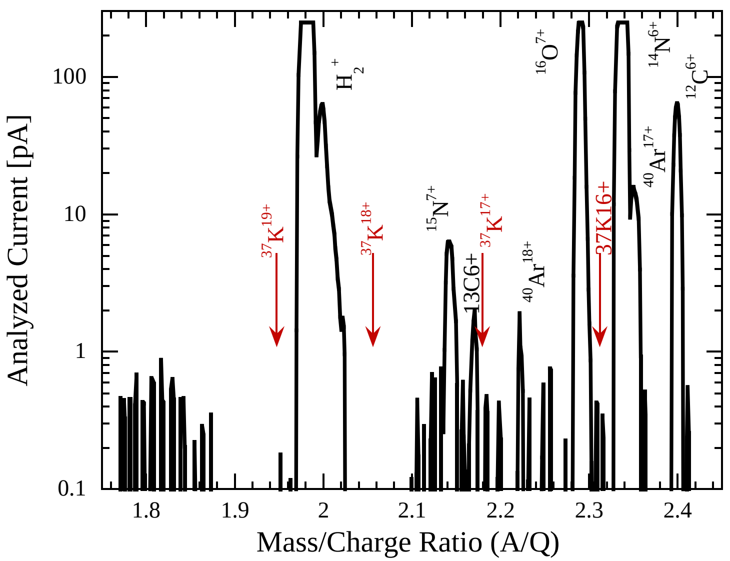
RIB beams

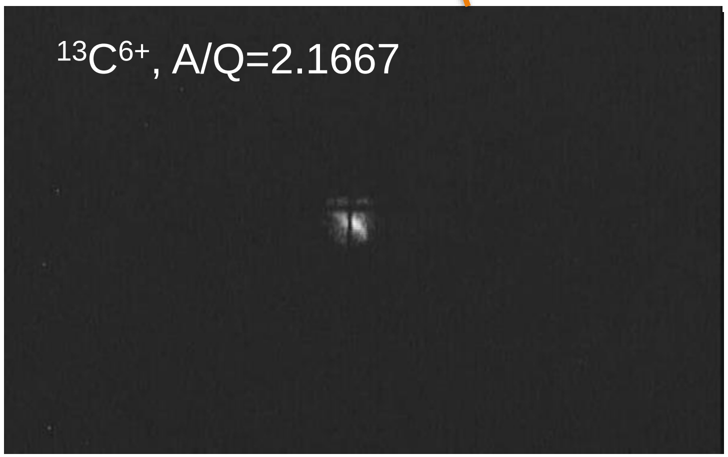
≈ 82% through RFQ

≈ 90% to target

Pilot Beams Are Used To Pre-Tune The Linac (Fixed Velocity Profile Used For Scaling)







MOPSM07, W. Wittmer et al.

Radioactive Ion Beam Measured at the experimental end station